CONTRIBUTION TO THE STUDY OF THE STRUCTURE OF THE IONOSPHERE

by Marcel Nicolet

Thesis, University of Brussels, 1945

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CONTRIBUTION TO THE STUDY OF THE STRUCTURE OF THE IONOSPHERE

Marcel Nicolet

INTRODUCTION

1. History

In 1901, Marconi established the first radio link between Poldhu in Cornwall and Saint-Jean de Terre-Neuve. The success of this transmission reinstated the hypothesis of Stewart (1878) and Schuster (1889), who had suggested that a part of the earth's magnetic field results from electrical currents in the upper atmosphere. Indeed, in 1902, Kennelly and Heaviside simultaneously proposed the existence of a conducting layer involved in the propagation of electromagnetic waves, whereas the works of Mac Donald, Lord Rayleigh and Poincaré (1904) revealed the impossibility of explaining the success of Marconi's experiment by diffraction. In 1912, Eccles, by introducing the ionization effect caused by solar radiation, proposed the fundamental theory of wave propagation in an ionized medium. Meanwhile, Austin (1911), after having carried out experiments on the variation in reception intensity with the distance from the broadcasting station, derived an empirical formula which was later rederived by Watson (1919), who solved the mathematical problem of wave propagation in a medium bounded by two concentric conducting spheres. The hypothesis of a conducting layer in the upper atmosphere was thus verified. Several years of rather disorderly experiments contributed some more refinements to the behavior of waves, and Larmor (1924), who extended Eccles' theory, studied the propagation in a very rarefied medium (absence of collisions) without external influence. Appleton (and Nichols and Schelleng) soon (1925) completed this theory by introducing the influence of the earth's magnetic field (magnetoionic theory) and, at the same time, demonstrated by suitable experiments the reflection by the atmosphere of waves emitted on the ground. In 1926, the influence of molecular collisions on the propagation was studied by Lassen. The introduction of this effect of frictional forces between neutral and charged particles revealed the relationship between the propagation and absorption of waves in the atmosphere. Finally, in 1927, Appleton gave a complete theory of the propagation of electromagnetic waves in a medium composed of charged and neutral particles subjected to the effect of collisions in the presence of a magnetic field.

This last work concluded the preliminary period of research. Experimentation was soon to benefit from new methods applicable to a systematic investigation of radio waves. The magnetoionic theory was born and was going to be developed for the purpose of studying the propagation of waves in the atmosphere. The physical study of the ionosphere could now begin.

2. Mathematical Theory (Ref. 1)

Under the impetus of the works of Appleton, the magnetoionic theory derived from the Maxwell-Lorentz theory developed very rapidly (Breit, Goldstein, Hartree, Baker, Green, and others) and as early as 1932 assumed the form which it still preserves today. The detailed determinations of M. Taylor, Bailey, Martyn and Booker, among others, form the basis of the study of electromagnetic wave propagation in the atmosphere, an absorbing medium stratified in homogeneous layers and composed of molecules and ions subjected to the influence of the earth's magnetic field.

A basic formula known as the Appleton-Hartree formula and resulting from the magnetoionic theory gives the complex expression

$$\left[\mu - \frac{ic\varkappa}{\omega}\right]^2 = 1 + \cfrac{2}{2(\alpha + i\beta) - \cfrac{s_T^2}{1 + \alpha + i\beta} \pm \sqrt{\cfrac{s_T^4}{(1 + \alpha + i\beta)^2} + 4s_L^2}} \tag{1}$$

where the symbols have the following meanings:

μ is the index of refraction;

$i = \sqrt{-1}$ and c, the speed of light;

$\varkappa$, the absorption coefficient;

$$\alpha \equiv - \frac{\omega^2}{\omega_c^2}$$

$\omega = 2\pi f$ (f = frequency of wave) designates the pulsation or gyrofrequency of the wave;

$$\omega_c^2 = \frac{4\pi N_E \varepsilon^2}{m}$$, where ω_c designates the critical pulsation, N_E the

electron concentration, and ε and m are the charge (absolute value) and mass of the electron;

$$s_L = \frac{\omega \omega_L}{\omega_c^2} \qquad s_T = \frac{\omega \omega_T}{\omega_c^2} \qquad s_H = \frac{\omega \omega_H}{\omega_c^2}$$

with $\omega_H = \frac{H_\epsilon}{mc}$, the vector H representing the earth's magnetic field, whose value is expressed in gauss and where ω_L and ω_T are orthogonal projections of vector ω_H, respectively, on the direction of propagation and on the plane of the wave;

$\beta = \frac{\omega v}{\omega_c^2}$, where v is the frequency of collisions of electrons with other particles;

If $\beta = 0$, because $v = 0$, the medium is not absorbing, and therefore, by considering only the real part, equation (1) is written as

$$\mu^2 = 1 + \frac{2}{2\alpha - \dfrac{s_T^2}{1+\alpha} \pm \sqrt{\dfrac{s_T^4}{(1+\alpha)^2} + 4\,s_L^2}} \qquad (2)$$

Let us now remember that $\mu = 0$ is considered the condition of the return (or incorrect terms widely employed at the present time, the condition of "reflection") of a wave emitted (vertically) into the atmosphere. It is seen that this condition is met if

$$\alpha + 1 = 0 \qquad (3)$$

when a positive sign is taken in the expression of the denominator in equation (2)

and if $\qquad \alpha = -1 \pm \sqrt{s_T^2 + s_L^2} = -1 \pm s_H \qquad (4)$

when a negative sign is taken.

In this latter expression (4), we see that if

$$\omega < \omega_c \ , \ \alpha = -1 + s_H$$
$$\omega > \omega_c \ , \ \alpha = -1 - s_H$$

Let $\alpha + 1 = 0$; in view of the meaning of α, we can write

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$$1 - \frac{\omega^2}{\omega_c^2} = 0$$

if the angular frequencies ω^2 and ω_c^2 are replaced by their expressions indicated in the definition of symbols, we find

$$N_E = \frac{\pi m f^2}{\varepsilon^2} \qquad (5)$$

i.e., a relation between the wave frequency and the electron concentration which makes it possible to determine the "critical frequency" as a function of the maximum electron concentration in the so-called "reflecting" layer.

Let $\alpha = -1 \pm s_H$; we then have

$$-\frac{\omega^2}{\omega_c^2} = -1 \pm \frac{\omega \omega_H}{\omega_c^2}$$

whence

$$\omega_c^2 = \omega^2 \pm \omega \omega_H$$

By replacing ω, ω_c, and ω_H by their values, we obtain

$$N_E = \frac{\pi m}{\varepsilon^2} \left(f^2 \pm f \frac{H\varepsilon}{2mc} \right)$$

or by setting $\omega_H = 2\pi f_H$,

$$N_E = \frac{\pi m}{\varepsilon^2} \left(f^2 \pm f f_H \right) \qquad (6)$$

where the upper sign corresponds to $f < f_H$ and the lower sign to $f > f_H$.

By studying the polarization, it can be shown that the case $\alpha + 1 = 0$ corresponds to what is called an "ordinary wave". We shall denote its critical frequency by f_0. On the other hand, if $\alpha = -1 \pm s_H$, the wave will be termed "extraordinary" and we shall denote its critical frequency by f_x. It will be noted that f_0 is the critical frequency of the wave in the case where there is no applied magnetic field, and this simple case corresponds to the case studied by Larmor.

Formulas (5) and (6) may therefore be written as

$$N_E = \frac{\pi m f_o^2}{\varepsilon^2} \tag{7}$$

$$N_E = \frac{\pi m}{\varepsilon^2} \left(f_x^2 \pm f_x f_H \right) \tag{8}$$

A study of equation (1) has also been made. It may be shown that equations (3) and (4) hold if the direction of propagation is of the quasi-transverse type, i.e., does not coincide with the direction of the magnetic field, provided that the frequency v of electron collisions be less than a critical frequency v_c.

$$v < v_c = \frac{\omega_T^2}{2\omega_L} = \frac{H_T^2}{2H_L} \frac{\varepsilon}{mc}$$

In conclusion, we see that thanks to the magnetoionic theory, we have the important relations (7) and (8), which make it possible to relate an observed quantity (the frequency of the wave) to the value of the electron concentration, an essential quantity for the study of the ionosphere.

3.   Experimental Results

Parallel to the development of the mathematical theory, experimental investigations have undergone improvements which provide various means of exploring the ionosphere. The echo method of Breit and Tuve (Ref. 2), the study of the minimum range of short waves by Hulburt (Ref. 3) and the examination of the interference of "reflected" waves by Appleton (Ref. 4) initiated the first fruitful investigations of the ionosphere. Furthermore, the echo method was adapted to automatic recording and now serves for the daily determination of the normal characteristics, the equivalent or virtual height and the critical frequency of the regions of the ionosphere.

The echo method consists in the quasi-vertical emission of very brief signals which are received at a small distance from the emitter. The time t between the respective receptions of the wave from the ground and of the wave "returned" by the atmosphere makes it possible to measure the equivalent height z of the ionized region by the relation $z = \frac{tc}{2}$, where c is the velocity of the wave. In addition, if the vertical soundings are performed by increasing frequencies, one finds that, for certain frequency intervals, the equivalent heights are more or less constant and thus define distinct ionized regions. Passage from one region

to another is characterized by an abrupt change in the equivalent
height. The frequencies associated with these changes are called cri-
tical frequencies and correspond, by virtue of relations (7) and (8)
between the number of electrons and the frequency of the wave, to the
maximum number of ionized particles in the defined strata. The exist-
ence of two principal regions has thus been demonstrated; these are the
E and F regions located at altitudes approximately of the order of 100
km and 300 ± 100 km.

The use of automatic observational systems now makes it possible
to obtain continuous experimental results at various points of the
globe. We shall cite the stations in Washington (Ref. 5), Huancayo,
Peru (Ref. 6), Watheroo, Australia (Ref. 6), Tromsö, Norway (Ref. 7),
whose regular publications permit a systematic study of the critical
frequencies (Ref. 8). Observations which cannot always be examined are
also made at Slough (Ref. 9), Calcutta (Ref. 10), Sydney (Ref. 11),
Tokyo (Ref. 12), Allahabad (Ref. 13), etc. These various data on the
ionosphere have been and are the subject of systematic research con-
cerned with the characteristic properties of the various regions as a
function of the physical conditions on the sun and the earth. Indeed,
it is found that the behavior (equivalent height and electron concen-
trations) of the various regions of the ionosphere depends on the ze-
nithal distance of the sun (diurnal, seasonal, and geographical effects),
on the disturbances of the solar atmosphere (storms and ionospheric
disturbances) and finally, on the 11-year solar activity.

4. Theoretical Results

The basic works of Chapman (Ref. 14) and of Hulburt (Ref. 15) pro-
vide the fundamentals of the conventional theory of the ionosphere. In
principle, this theory, which underlies the interpretation of certain
observational data, is as follows:

A monochromatic radiation of intensity S, emitted by the sun, pene-
trates into the atmosphere, which is assumed to have a uniform composi-
tion over the entire region exposed to the radiation. No a priori hypo-
thesis is made on the nature of the solar radiation except that the ab-
sorbed energy dS during the passage of the radiation S through a layer
of thickness dz is proportional to the intensity·of the radiation, to
the thickness of the layer, and to the concentration of the absorbing gas.
Hence, we write

$$dS = \frac{AS}{\sin h_\odot} e^{-z/H} dz \tag{1}$$

where Adz is the fraction of the radiation absorbed in the layer of
thickness dz located at altitude z = 0, and where $h_\odot$ is the angle of

altitude of the sun above the horizon and H is the height of the homo-
geneous atmosphere given by

$$H = \frac{kT}{mg} \qquad (2)$$

T and m being the absolute temperature and the molecular mass, which are
constant, k being Boltzmann's constant, and g the acceleration due to
gravity.

Integration of (1) gives

$$S = S_\infty \; e^{-\frac{AH}{\sin h_\odot} \; e^{-z/H}} \qquad (3)$$

where S_∞ is the value of S at the top z = ∞ of the atmosphere. The

absorption at altitude z is thus given, based on (1) and (3), by

$$\sin h_\odot \frac{dS}{dz} = A S_\infty \; e^{-z/H} \; e^{-\frac{AH}{\sin h_\odot} \; e^{-z/H}} \qquad (4)$$

Assuming that the number of electrons produced at altitude z per

cm^3 per second is proportional to $\frac{dS}{dz} \sin h_\odot$, we can write that the elec-

tron production P per cm^3 per second, based on (1) and (4), is given by

$$P_z = \varphi A S_\infty \; e^{-(z/H + \frac{AH}{\sin h_\odot} \; e^{-z/H})} \qquad (5)$$

where ϕ is the proportionality factor.

We see immediately that P_z is maximum $h_\odot = 90^\circ$ for

$$e^{z^*/H} = AH \qquad (6)$$

and hence, the value of the maximum of P, P* is given by (5) and (6)

$$P^* = \frac{\varphi S_\infty}{He} \qquad (7)$$

where e = 2.718.

From (5), (6), and (7), we deduce

$$P_z = P^* \, e^{1 - \dfrac{z - z^*}{H} - \dfrac{e^{-\dfrac{z - z^*}{H}}}{\sin h_\odot}} \tag{8}$$

By setting

$$\frac{z - z^*}{H} = \zeta \tag{9}$$

we finally obtain

$$P_z = P^* \, e^{1 - \zeta - \dfrac{e^{-\zeta}}{\sin h_\odot}} \tag{10}$$

which is the relation between the ratio of the productions P_z and P^*,

the value of ζ and the angle of altitude $h_\odot$ of the sun.

At a given instant, the variation of the number of electrons is the difference between the number of electrons produced and the number of those which disappear. By hypothesizing that the electrons disappear via recombination with positive ions, the variation of the electron concentration N_E with time t is given by

$$\frac{\partial N_E}{\partial t} = P - r N_E^2 \tag{11}$$

where r is the recombination coefficient.

Let us note that by writing relation (11), we admit implicitly that the number of positive ions is equal to the number of electrons.

By considering the case of equilibrium $\dfrac{\partial N_E}{\partial t} = 0$, we deduce (12) and (13), successively

$$N_E = \sqrt{\frac{P^*}{r}} \, e^{1/2 \left(1 - \zeta - \dfrac{e^{-\zeta}}{\sin h_\odot} \right)} \tag{12}$$

and

$$N_E = N_E^* \, e^{1/2 \left(1 - \zeta - \dfrac{e^{-\zeta}}{\sin h_\odot} \right)} \tag{13}$$

if N_E^* is the electron concentration at maximum production when $h_\odot = 90^\circ$.

Expressions (12) and (13) define a conventional ionized region, i.e., the vertical distribution of the electron concentration in an atmosphere of constant temperature and molecular mass.

From equation (13) we immediately find that the electron concentration reaches its maximum when

$$\sin h_{\odot} = e^{-\zeta_{max}} \qquad (14)$$

If we denote by $(N_E)_{max}$ the value of the maximum electron concentration of an ionized region, we immediately have from (12) and (14),

$$(N_E)_{max} = \sqrt{\frac{P^*}{r}} (\sin h_{\odot})^{1/2} \qquad (15)$$

or, from (13) and (15)

$$(N_E)_{max} = N_E^* \, e^{-1/2 \, \zeta_{max}} \qquad (16)$$

From expressions (13), (14), and (16), we deduce

$$N_E = (N_E)_{max} \, e^{1/2} \left[1 - (\zeta - \zeta_{max}) - e^{-(\zeta - \zeta_{max})} \right] \qquad (17)$$

or

$$N_E = (N_E)_{max} \, e^{1/2} \left[1 - y/H - e^{-y/H} \right] \qquad (18)$$

with

$$y = (\zeta - \zeta_{max})H = z - z_{max} \qquad (19)$$

In the case where the phenomena in the vicinity of the maximum concentration are taken into consideration, we can keep only the first two terms of the series expansion of $e^{-y/H}$, as does Appleton (Ref. 16). Hence, we have the approximate relation

$$N_E = (N_E)_{max} \left[1 - \frac{y^2}{4H^2} \right] \qquad (20)$$

which gives, at a first approximation, a parabolic distribution of the electron concentration.

Consequently, under the influence of the sun, the electron concentration (cf. (15)) should increase beginning at sunrise and should reach a maximum at local noon. Also, a seasonal effect should be observed which brings a corresponding maximum to the summer solstice and a minimum

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to the winter solstice. Furthermore, the electron concentrations should be highest at the lowest latitudes. Finally, the vertical distribution (cf. (20)) of the electron concentration should give the height of the homogeneous atmosphere.

Appleton (Ref. 16) has shown how the E region could be generally interpreted by the conventional theory, where the electron concentration is proportional to the square root of the sine of the angle of altitude of the sun. For the F region, it is necessary to introduce additional hypotheses (Appleton, Ref. 16; Berkner, Ref. 17; Bradbury, Ref. 19; Martyn, Ref. 22), which most often should be considered as arbitrary. Whatever the laws governing the formation of an ionized region, however, one must look for the origin of the various regions observed, i.e., determine which of the atoms and molecules of the atmosphere are likely to induce the formation of an ionospheric region. Moreover, once the theoretical study of the formation and origin of a region has been concluded, the experimental values of the recombination coefficients should correspond to the values introduced into the equations. The latter two points have been made the subject of special study by Appleton (Ref. 16), Berkner (Ref. 17), Bhar (Ref. 18), Bradbury (Ref. 19), Hulburt (Ref. 15), Lassen (Ref. 20), Massey (Ref. 21), Martyn (Ref. 22), Mitra (Ref. 23), Tukada (Ref. 24) and Wulf and Deming (Ref. 25).

The investigation of the origin of ionospheric regions has been carried out particularly by Hulburt, Bhar, Mitra, Wulf and Deming. The sun is considered to be a black body at 6000°K; hypotheses are introduced on the composition and vertical distribution of the constituents of the upper atmosphere. On this basis, the state of ionization of O_2, N_2 and O compared with the observation reveals the various difficulties involved in a correct interpretation.

In the determination of the recombination coefficient, the study is based on an examination of the nocturnal conditions, where the electron concentration is given, in the case of the conventional theory, by

$$\frac{\partial N_E}{\partial t} = - r N_E^2 \qquad (21)$$

An experimental study of the decrease in ionization during the night leads to a recombination coefficient ($\sim 2 \cdot 10^{-9}$) which is higher than that given by the theory ($\sim 2 \cdot 10^{-12}$).

By assuming that the number of positive ions (N^+) is greater than that of the electrons, Appleton (Ref. 16) and Massey (Ref. 21) have shown that equation (21) should be written as

$$\frac{\partial N_E}{\partial t} = - \, r N^+ N_E = -\alpha N_E^2 \tag{22}$$

Indeed, if it is assumed that the number of positive charges (positive ions) is equal to the number of negative charges (negative ions N^- and electrons), it follows that

$$N^+ = N^- + N_E \tag{23}$$

and the effective recombination coefficient α may be greater than r, since one can write

$$\frac{\partial N_E}{\partial t} = - \, r N^+ N_E = - \, r N_E^2 \left(1 + \frac{N^-}{N_E}\right) = - \, \alpha N_E^2 \tag{24}$$

Values from 100 to 1000 of the ratio N^-/N_E, which may exist in the

E region (cf. Massey, Ref. 21) make it possible to determine the values of α which approach the night recombination coefficient.

The above is a summary of the acquired theoretical data. They have permitted the elucidation of certain difficulties, indicating, at the same time, the extreme complexity of the general problem of the structure of the ionosphere and of its variations.

5. Object of the Work

In the present state of our knowledge of the constitution of the sun and of the atmosphere and of the recent progress in atomic and molecular theory, it is possible to attempt a solution of the problem of the ionosphere in its general aspects. Thus, our work is primarily concerned with an examination of the properties of the ionosphere based on the results of observations of the propagation of electromagnetic waves, results which can be used owing to continuous and detailed publications. Furthermore, after having presented the ionospheric characteristics, we examine the spectral properties of the sun, taking into account the various results of the theory and observation, and thus deduce the radiations which play an effective part in the ionization of the atmosphere. In addition, results of observations of the emission of night airglow and auroras lead us to a determination of the atomic and molecular constitution of the upper layers, and enable us to refine certain important points concerning the vertical distribution of the atoms and molecules. Finally, a determination of the principal mechanisms relating the equilibrium of ions and electrons is undertaken with the aid of kinetic and quantum properties for the purpose of applying them to the atmosphere. Thus, the

synthesis of these various results enables us to discuss the ionospheric properties. Consequently, we divide our work as follows:

    Chapter I. Observation of the Ionosphere.
    Chapter II. Solar Radiation.
    Chapter III. Constitution and Composition of the Atmosphere.
    Chapter IV. General Ionization Equations.
    Chapter V. Physical Interpretation of the Ionosphere.
    General Conclusions.

    In conclusion, I am happy to be able to thank my teacher, Professor P. Swings. After having initiated me into scientific research, he has often given me valuable lessons with a special kindness. I am wholly indebted to him.

    During the editing of this work, I have often asked for the assistance of Messrs. Lahaye and Van Mieghem. Their advice and suggestions have been very useful to me and I shall not forget that their particular helpfulness enabled me to conclude this study successfully.

    I am pleased to be able to include in my gratitude the Belgian government and the Fondation Universitaire. It is through their generosity that I have been able to travel abroad, where I conducted my preliminary research.

    My thanks are also addressed to Professor P. Gotz, Director of the Lichtklimatisches Observatorium at Arosa, for his amiable hospitality and his affectionate solicitude.

November, 1944.

CHAPTER I.   OBSERVATION OF THE IONOSPHERE

Section 1.   Introduction

In general, observation reveals the presence of two principal ion-
ized regions called E and F regions. The first region, E, is situated
at an altitude close to or somewhat above 100 km, whereas the F region
is often subdivided into the two regions F_1 and F_2 located respectively

at altitudes of the order of 200 and 300-400 km. The heights of these
ionization maxima represent average values which vary with the latitude
and the seasons.

In a particular case (for example, at the Equator) the distribution
of the ionization state may be succinctly described as follows (see
Figure 1): near the ground, cosmic and terrestrial sources produce a
few thousand ions per cm^3. As one goes up into the troposphere and
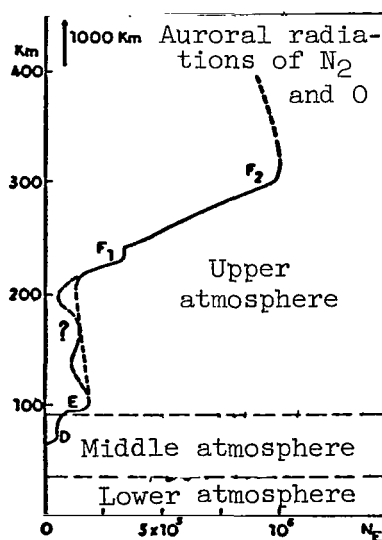

Figure 1. Schematic representation of the ionosphere.
Abscissas: electron concentration (number of elec-
trons per cm^3). Ordinates: altitude in km

stratosphere, the ion concentration increases up to an altitude of 16-18 km. Although some effects on radio waves seem to have been observed in these regions, it appears, according to O. H. Gish and H. G. Booker (Ref. 26) that there is no intense ionization in the stratosphere or troposphere. Starting from 60 km, the experimental results indicate the existence of an ill-defined ionized region generally referred to as the D region. At about 100 km, the increase is so considerable that the

maximum concentration reached is of the order of 10^5 electrons; this is the E region. Beyond 100 km, the ionization, after a slight decrease, increases again and reaches a high value which exceeds that of the E layer (approximately double); this is the F_1 region. After a slight de-

crease, the most important maximum appears, which corresponds to the F_2

region; its electron concentration exceeds 10^6 electrons. These various regions possess essentially different properties, which we shall examine successively. Moreover, the purpose of this chapter is to synthesize the most important experimental results and to bring out their essential features.

Section 2. The D Region

    Results obtained on the state of ionization of the D region are scarce. Mitra and Syam (Ref. 27) have observed echoes corresponding to

electron concentrations of the order of $5 \cdot 10^4$ electrons per cm^3. According to Budden, Ratcliffe and Wilkes (Ref. 28), the number of elec-

trons at about 67 km is of the order of 300 per cm^3 (average conditions for the southeast of England) and permits the return of long waves of 18.8 km. At the Huancayo and Watheroo stations, a systematic examination of the minimum critical frequency at which the "reflections" of the waves are recorded provides other indications. Indeed, one finds that the variation of this minimum critical frequency is generally analogous to the variation of the critical frequency of the E region (see Section 3, E region). The fact that there exists a minimum critical frequency above which the waves are no longer returned indicates that an "absorption" is involved. According to a mathematical study of the propagation of electromagnetic waves in an ionized medium, this "absorption" corresponds to the damping of waves due to collisions between molecules and electrons accelerated by the electric field. According to the observations, this damping has its maximum above the E region, and this atmospheric area may be considered to correspond to the D region. In addition, during the sudden fade-out of short waves (see Section 6), one is

still dealing with a damping action, and the D region is involved owing to an increase in ionization.

Section 3. The E Region

The E region is an ionized layer whose properties are known fairly well, since its different variations are relatively simple.

Altitude of the Ionization Maximum

The average equivalent altitude of the ionization maximum depends both on the latitude and the seasons. At Huancayo, Peru, z = 100 km; at middle latitudes (Washington, Slough), z = 115 km in summer and 125 km in winter, and, at high latitudes, z = 125 km during the polar winter and of the order of 100 km in summer.

In short, the altitude of the ionization maximum of the E layer varies in inverse proportion with the height of the sun and its presence above the horizon.

Diurnal Variation

Figure 2 shows a typical curve of the maximum electron concentration $(N_E)_{max}$, which varies synchronously with the height h of the sun above the horizon. The following conclusions are drawn directly from the observation: (1) the diurnal ionization maximum takes place at noon when the height of the sun is maximum; (2) the values of $(N_E)_{max}$ are practically symmetrical with respect to noon; (3) $(N_E)_{max}$ is proportional to the square root of the sign of the height of the sun (for $h_\odot > 0^O$).

In short, the observations yield the law

$$(N_E)_{max} = C \sqrt{\sin h_\odot} \qquad (I.1)$$

so long as $h_\odot \neq 0$. The meaning of the constant is obtained by setting $h_\odot = 90^O$ in equation (I.1); it corresponds, therefore, to the maximum electron concentration of the E region at the Equator and at the equinox.
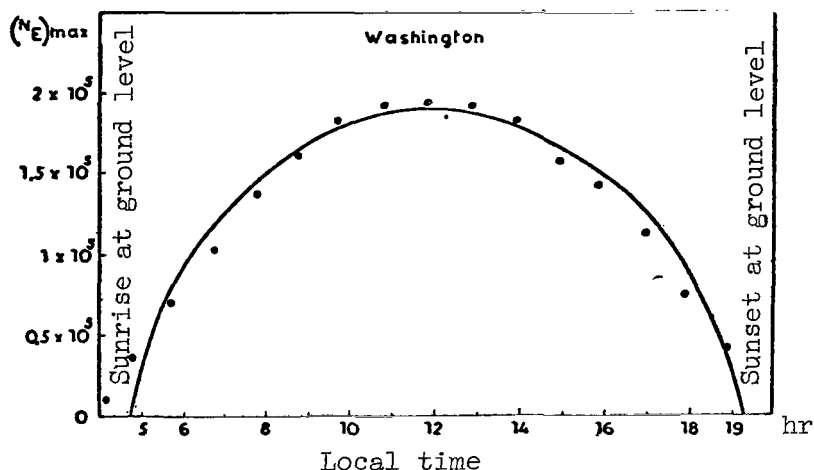
Figure 2. Diurnal variation of the maximum electron concentration of the E region at Washington during May 1938.

The points represent data deduced from observation of critical frequencies (monthly averages), while the curve was traced in accordance with the law (I.1)

Seasonal Variation

The observational results obtained in the course of one year at the same station show that the summer values of $(N_E)_{max}$ are always greater than those of the winter. The diurnal variation of $(N_E)_{max}$ is always symmetrical with respect to noon and the values at sunrise are identical to those at sunset. A consideration of the mean monthly values of $(N_E)_{max}$ at noon makes it possible to determine simply the variation of the electron concentration as a function of the seasons. From Figure 3, it is seen that the maximum electron concentration follows the same law of variations during the year as during a day, i.e., C being a suitably selected constant,

$$(N_E)_{max} = C \sqrt{\sin h_\odot} \qquad (I.2)$$

Let us note, nevertheless, that the mean monthly values of the electron concentrations do not fall rigorously on the curve drawn in accordance with the law (I.2). These deviations will be studied later during an examination of the long-period variation.
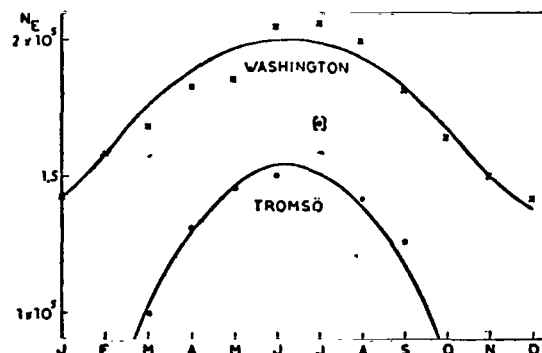
Figure 3. Annual variation of the maximum electron
concentration at noon for the stations of Washington
(lat. 39°N) and Tromsö (lat. 66.7°N) during the year
1938.
   The points and crosses represent data deduced from
observation of critical frequencies; the curves were
traced in accordance with the law (I.2)

Geographical Variation

Although all the stations distributed over the globe present the
same diurnal and seasonal variations, it is nevertheless true that
during a study made as a function of the latitude, the constant C in-
troduced in order to satisfy equality (I.2) varies from one station to
another. In other words, when the results obtained for different sta-
tions as a function of the latitude are compared, the continuous decrease
of the value of C (in going from the Equator to the pole) reaches 30 per-
cent. This result indicates, therefore, that atmospheric conditions
which are functions of the latitude add to the solar effect itself.

Long-Period Variation

Among the long-period variations which can be expected, all of the
attention should be focused on the variation which should result from
the 11-year solar activity. In Figure 4, we have shown the mean monthly
values of $(N_E)_{max}$ from 1935 to 1940 at noon, observed at the Washington

station. A simple inspection of the graph shows that a long-period
variation is superimposed on the seasonal variation. The former is
parallel to the variation of the solar activity. Recent determinations
have revealed that there is a good correlation (Ref. 29) between the
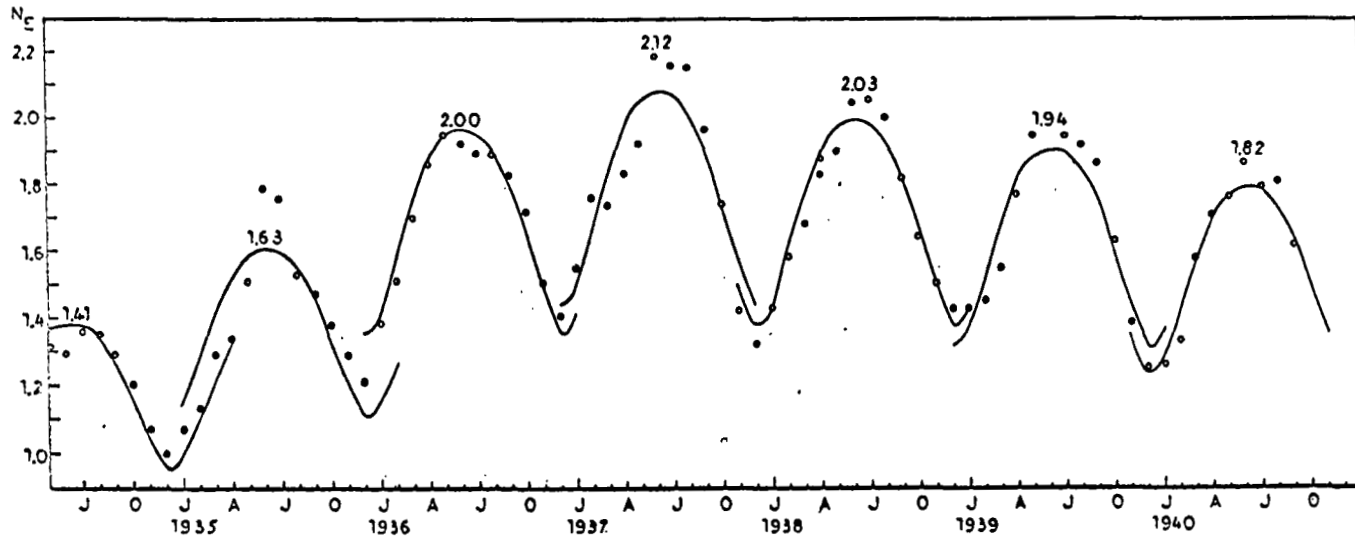
Figure 4. General variation of the maximum noon electron concentration of the E region at the Washington station.

The points represent observational data. The curves were traced with the aid of relation (I.2), where different values of constant C were employed. The figures above each curve are values of C.

It will be noted that a long-period variation manifested by a concentration maximum in 1937 is superimposed on the seasonal variation. This is the 11-year variation

average ionization values and the relative sunspots numbers of Wolf. It should be noted, however, that there is no relation between the daily variations of the ionization and the number of spots, which indicates that there is no correspondence whatever between a given spot and the ionization of the E region.

The curves of Figure 4 have been traced by assuming that C is a constant during a year. The scatter of the points representing the observational data is due to the effect of the solar activity. In order to determine this effect qualitatively, we have added in Figure 5 the data for the three stations of Huancayo, Watheroo and Washington during the period of January 1939 to June 1940, for which simultaneous observations are available. From formula (I.2) we have deduced the monthly values of C

$$\frac{(N_E)_{max}}{\sqrt{\sin h_\odot}} = C$$

where $(N_E)_{max}$ is deduced from the values of the critical frequency observed and $\sin h_\odot$ is determined by the usual astronomical formulas. In addition, we have used qualitative data, published in the Quarterly Bulletin of Solar Activity, on the facular plages of ionized calcium. One can readily see from Figure 5 that these fluctuations of C at the three stations are roughly parallel to those of the arbitrary numbers of the facular plages.

In short, there is a detailed correspondence between the solar activity defined by the facular plages and the maximum electron concentration of the E region.

Nocturnal Variation

After sunset, the electron concentration, being no longer subjected to the action of the sun, gradually diminishes and attains a minimum at the end of the night. In this case, assuming the variation law (see note at the end of this subsection)

$$\frac{\partial N_E}{\partial t} = - \alpha N_E^2 \qquad (I.3)$$

where α is the effective recombination coefficient, we find (Ref. 30) that the decrease corresponds to a value of $\alpha = 2$ to $4 \cdot 10^{-9}$.
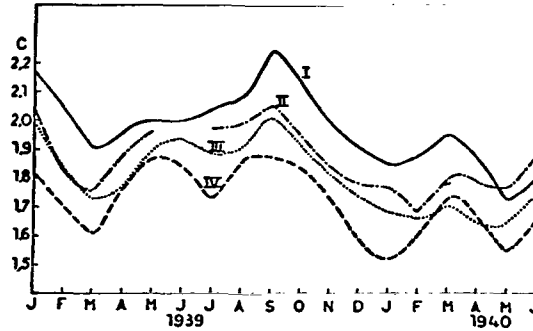
Figure 5. Effect of solar activity on the ionization state of the E region.
 Curve I, Huancayo, Peru (lat. 12° N); curve II, Washington (lat. 39° N); curve III, Watheroo, Australia (lat. 30° S); curve IV, square root of arbitrary numbers of facular plates of ionized calcium

This determination of the effective recombination coefficient makes it possible to state what the precise conditions are to which the nocturnal ionization is subjected. We shall see further on that this value of the effective coefficient is lower than the effective coefficient during the day.

NOTE. It can be shown that, if the disappearance of the electrons is governed by a recombination mechanism, i.e., by the association between a positive ion and a free electron, we have

$$\frac{\partial N_E}{\partial t} = -rN^+N_E$$

where r = constant, called the recombination coefficient, N^+ is the concentration of positive ions, and N_E is the electron concentration.

If $\qquad\qquad N^+ = N_E, \dfrac{\partial N_E}{\partial t} = -r N_E^2$

i.e., this is a law of electron variation proportional to the square of the electron concentration.

If $\qquad\qquad N^+ \neq N_E, \dfrac{\partial N_E}{\partial t} = -\alpha N_E^2 \qquad\qquad$ (A)

which is a law similar to the preceding one, where α is an effective recombination coefficient greater or smaller than r, depending on whether

$N^+ > N_E$ or $N^+ < N$. If the disappearance of electrons takes place via attachment (electron captured by a neutral atom), i.e., is directly proportional to the electron concentration, we necessarily have

$$\frac{\partial N_E}{\partial t} = -\, aNN_E = -\, \beta N_E \qquad (B)$$

where a is the coefficient of attachment and N is the number of neutral atoms per cm^3.

In a region of the atmosphere where the law of disappearance of electrons is unknown a priori, the experimenters interpret their observations by a law of variation proportional to the square of the electron concentration.

However, if the attachment is effective, in order to understand the experimental results expressed by a law of variation proportional to the square of the electron concentration, one should write

$$\frac{\partial N_E}{\partial t} = -\, \frac{aNN_E^2}{N_E} = -\, \alpha N_E^2$$

where α should be regarded as the equivalent recombination coefficient which will not be constant but will be a function of N and N_E.

If the two mechanisms take place simultaneously, in order to separate the effects of the two processes of recombination and of attachment, one can write

$$\frac{\partial N_E}{\partial t} = -\, \alpha N_E^2 -\, \beta N_E$$

Variation During Eclipses

The solar eclipses permit a study of the variation of ionization in a relatively simple manner, since the conditions of ionization vary very rapidly. Multiple observations (Ref. 31) made in various regions of the globe have lead to quantitative determinations of the electron variation. By assuming a variation law such that

$$\frac{\partial N_E}{\partial t} = \Gamma \sin h_\odot -\, \alpha N_E^2 \qquad (I.4)$$

where P represents the electron production for $h_\odot = 90^\circ$ and where αN_E^2

corresponds, as before, to the electron decrease due to spontaneous recombination, it is possible to obtain the value of α by taking into account the darkened fraction of the solar disk. In Figure 6, we reproduce the possible electron concentrations of the E region calculated by Hulburt (Ref. 32) for different values of an effective recombination coefficient α. The results obtained during the observation (Ref. 33) showed that the electron concentration decreased during the eclipse to about 25 percent of the normal value. This indicates (Figure 6) that the mean value of an effective recombination coefficient is approximately $2 \cdot 10^{-8}$. However, the fact that the ratio of the decrease should be greater and the fact that the instant of the minimum electron concentration appears in the middle of the totality reveal higher values

of the α coefficient, values which should be $\geqslant 10^{-7}$. Furthermore, Dellinger (Ref. 33) reports that the ionization increased before the third contact.

In short, these results can be interpreted only if one assumes a variation of the recombination coefficient during the course of the eclipse. As long as the eclipse is not complete, the recombination coefficient is very high (10^{-7} or more), but the onset of totality is associated with the onset of night conditions, and the value of the coefficient decreases. Thus, the minimum ionization is no less than 25 percent of the normal value. Furthermore, the value of the term αN_E^2 is very high as compared to $\dfrac{\delta N_E}{\delta t}$, and the equilibrium conditions may be considered in a practical case for the sake of calculation.

The results obtained during the eclipses make it necessary to consider the diurnal variation of the ionization by taking into account the values of the recombination coefficients. In Figure 7, we reproduce the calculated curves given by Hulburt (Ref. 30), where $\alpha = 2 \cdot 10^{-9}$, 10^{-8} and ∞. The only reasonable conclusion is the following: the observations are best represented by a value[1] of the recombination

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[1]Determinations made by Appleton (Proc. Roy. Soc. London, 162, 451, 1937) and by Best, Farmer and Ratcliffe (ibid., 164, 96, 1938) indicate that during the day $\alpha \geqslant 2 \cdot 10^{-8}$.
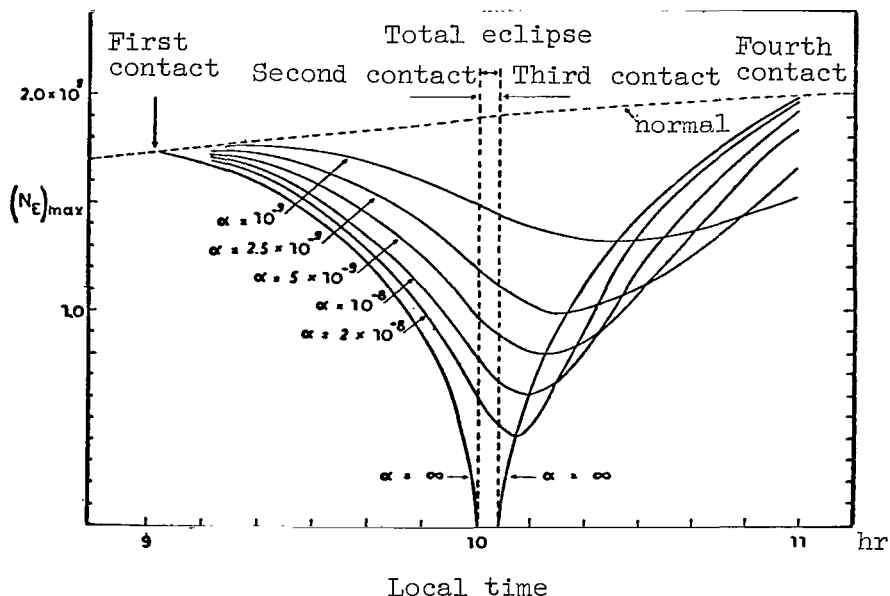
Figure 6. Theoretical values of the maximum electron concentration of the E region at Pernambuco, Brazil, for the solar eclipse of 1 October 1940, according to E. O. Hulburt, Phys. Rev., 55, 646, 1939.

The various curves were calculated for values of $\alpha = 10^{-9}$ to $2 \cdot 10^{-3}$. The extreme case, where the electron production is at any instant in equilibrium with the recombination, is represented by the curve $\alpha = \infty$

coefficient in excess of $2 \cdot 10^{-8}$. In other words, the value of $\dfrac{\partial N_E}{\partial t}$ is so slight compared to P and to αN_E^2 during most of the day that the equilibrium may be considered to be practically established at every instant t between the production and the recombination of electrons.

Consequently, the value of the recombination coefficient of the E region varies between 10^{-7} and $2 \cdot 10^{-9}$. Well-defined and constant during the night (2 to $4 \cdot 10^{-9}$), it is markedly greater than this value during the day, and various observations, the diurnal variation in general and the variation during solar eclipses in particular, reveal in all cases values in excess of $2 \cdot 10^{-8}$ and even 10^{-7}.
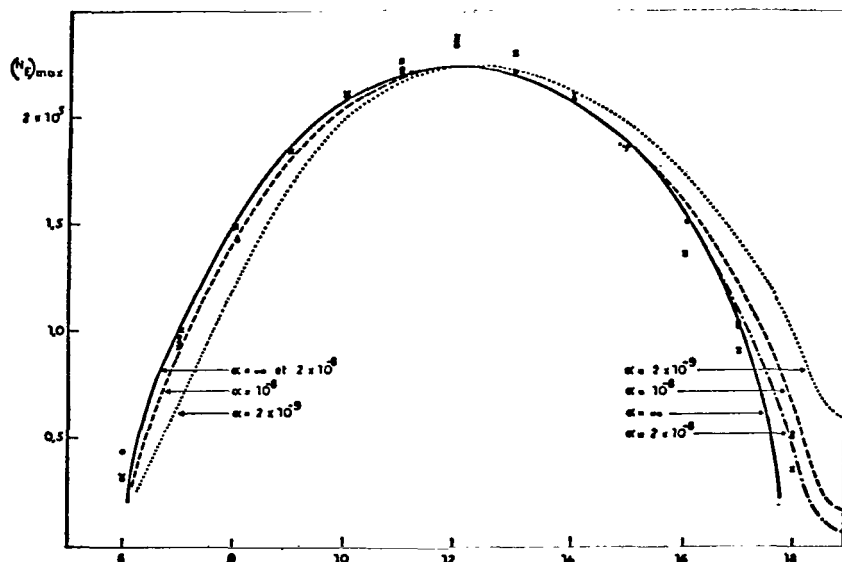
Figure 7. Comparison between observations made at Huancayo and the theoretical curves traced for different values of α, by E. O. Hulburt, Phys. Rev., 55, 639, 1939.

The circles, points and crosses represent the observed mean monthly values of the electron concentration of the E region for January, February and March 1938, respectively

Abnormal Variations

The particular conditions characterizing the abnormal conditions are given various names such as "abnormal region", "abnormal ionization", "intense ionization", and "perturbed layer". Apparently, there exists a whole gamut of abnormal variations whose physical conditions cannot always be precisely determined. However, it may be assumed that in certain cases the abnormal ionization results from electron "clouds" within the normal E region. The altitude of these clouds is generally lower (by approximately several kilometers) than the maximum level of the E region. This abnormal ionization appears both during the day and at night and lasts for time intervals varying from a few seconds to one hour. Furthermore, abnormal behavior seems to be manifested in the case of a climax (especially at high and middle latitudes) by ionized clouds of high concentrations which exceed the normal ionization of the E layer

and reach 10^6 electrons per cm^3.

Simple Perturbations

Among abnormal types of behavior there exist some perturbed conditions which are well-defined and which differ from the irregularities cited in the preceding paragraph; these are the perturbations corresponding to the sudden short wave fade-out and to the correlative reinforcement of long waves. This phenomenon, which is simultaneous with chromospheric eruptions, can be interpreted by assuming a sudden increase in ionization at the base or above the E region, an increase which causes an absorption of short waves and a better "reflection" of long waves. A study of this ionospheric perturbation appears very interesting because it also corresponds to a perturbation in the normal diurnal variation of the earth's magnetic field and should make it possible to deduce the origin of the diurnal solar variation from the terrestrial magnetism. The characteristics of this perturbation should, therefore, be determined (see Section 6).

Ionospheric Storm

This ionospheric perturbation, about which knowledge is only beginning to progress beyond the descriptive stage (Ref. 34) should be considered as a disruption of equilibrium in the upper atmosphere. It is actually the cause of the magnetic storm, for which descriptions are very numerous. Since no quantitative observational data have been published as yet, it is not presently possible to indicate the exact nature of this perturbation or, therefore, to look for a quantitative theoretical solution of this problem.

Section 4. The F_1 Region

The F_1 region can be observed only during part of the day, and the

characteristic properties of the variation of ionization are then analogous to those of the E layer. Also, the diurnal, seasonal and 11-year variations of the two regions are comparable. Therefore, the same considerations apply to these variations of the two regions, and they should be interpreted by analogous theoretical relations. The recombination

coefficient is of the order of 10^{-8}. However, the disappearance of the F_1 layer when the height of the sun is relatively low indicates a peculiar behavior characteristic of this layer. During the night, the complete disappearance of the F_1 layer, even at the Equator and at the low

latitudes, should be due to the variation in the value of the recombination

coefficient, which at this level induces a decrease in electron concentration such that it is lower than that of the E region.

Section 5. The F_2 Region

In contrast to the simple variations of the E and F_1 regions, the ionization of the F_2 region presents irregularities which observation has not yet been able to follow completely. Moreover, fluctuations of the electron concentrations are frequent and present numerous anomalies. However, even if these anomalies are excluded, the various continuous variations are complex and have not yet been elucidated. In the discussion which follows, the character of the principal phenomena will be described in order to permit a physical interpretation of the most general results.

Altitude of the Ionization Maximum

Whereas the virtual heights of the ionization maxima of the E region correspond fairly well to the real heights (thin layer), this is no longer the case of those of the F_2 region, whose determination is strongly influenced by the effect of the lower layers (absorption). In fact, the variations of the virtual heights of the F_2 region do not correspond to the variations of the actual heights, i.e., the altitudes of the maxima of N_E; attempts are being made to approximate these altitudes (Ref. 35). Figure 8 is a typical example of the different variations of the real and virtual heights. Whereas the altitude of the E and F_1 regions diminishes under the solar influence, the F_2 region shows rather an inverse variation of the virtual height. Indeed, in the course of the year, the ionization maximum at the same station varies in altitude as the height of the sun above the horizon. On the basis of the initial results (Ref. 35), it would seem that the real altitude increases by about 50 km from winter to summer. In addition, the latitude effect also appears to be in the same direction; observations made at Huancayo, Watheroo and Washington tend to show that the altitude of the ionization maximum at Huancayo (Equator) is definitely greater than the respective altitudes at Watheroo (Australia) and Washington. The real altitudes of the ionization maximum of F_2 at Washington and Watheroo are of the
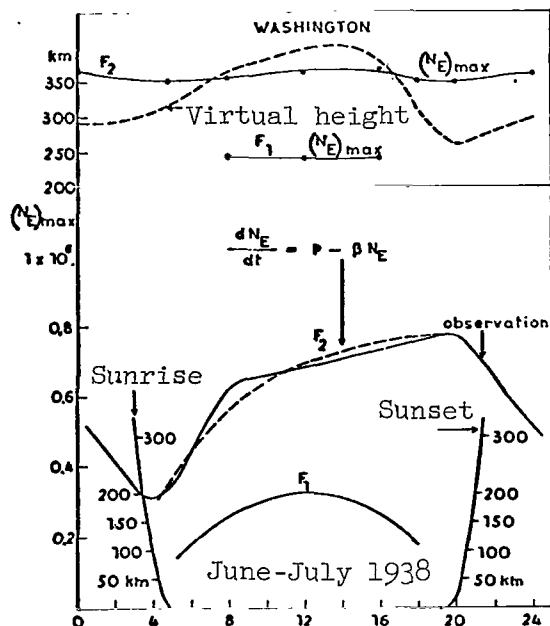
Figure 8. Values of the maximum electron concentration and of its altitude in the F_1 and F_2 regions at Washington in June-July 1938, according to F. L. Mohler, Jour. Res. Nat. Bur. Stand., 25, 507, 1940

order of 350 km, whereas those corresponding to Huancayo are on the order of 450 km. Since the results published on the real heights are still incomplete and occasionally in mutual disagreement, it is not possible to carry out a more extensive examination. After sunset, the altitude of the F_2 region gradually increases, and the duration of the increase

seems to be shorter the higher the normal altitude of the layer. After this increase, generally before midnight, the height of the layer remains constant or decreases until sunrise (see Figure 8).

Diurnal Variation

If we consider the diurnal variation of the electron concentration of all the stations distributed over the surface of the globe we find all types of variations, which shows that the influence of the sun is not expressed by laws as simple as those in the case of the E layer. Typical cases include a distinct decrease in the electron concentration about noon, when the sun is at its maximum height. This abnormal decrease

can therefore be related only to the structure of the atmosphere, which changes during the day and with the latitude. Hence, an attempt should be made to relate the electron variation to the variation of the height of the region, but no accurate study has as yet been undertaken. However, an investigation made by F. L. Mohler (Ref. 35) into some simple cases observed in Washington (Figures 8 and 9) makes it possible to draw certain conclusions. Indeed, by admitting a priori the law

$$\frac{\partial N_E}{\partial t} = P \sin h_{\odot} - \alpha N_E^2 \qquad (I.4)$$

we obtain $\alpha = 0.8 \cdot 10^{-10}$ for October 1938, and $\alpha = 1 \cdot 10^{-10}$ for November 1938.

For June-July 1938, if we assume that

$$\frac{\partial N_E}{\partial t} = P - \beta N_E \qquad (I.5)$$

we find $\beta = 6 \cdot 10^{-5}$.

For September 1938, if we set

$$\frac{\partial N_E}{\partial t} = P - \alpha N_E^2 \qquad (I.6)$$

we have $\alpha = 0.7 \cdot 10^{-10}$.

By considering the values of the electron concentration for the same hour angle, before noon (a.m.) and after noon (p.m.) during the month of October, 1938, Mohler obtained the average value $\alpha = 0.9 \cdot 10^{-10} \pm 0.2 \cdot 10^{-10}$, by writing

$$\left(\frac{\partial N_E}{\partial t}\right)_{a.m.} - \left(\frac{\partial N_E}{\partial t}\right)_{p.m.} = [(N_E^2)_{p.m.} - (N_E^2)_{a.m.}]\alpha \qquad (I.7)$$

a relation which results from (I.4).

Using the same procedure, Appleton (Ref. 30) had already found the value $0.84 \cdot 10^{-10}$ for the recombination coefficient in England.

Finally, a comparison of the values for the sunrise and sunset for 20 months of the 1937-1939 period yields the values $\alpha = 0.9 \cdot 10^{-10} \pm$
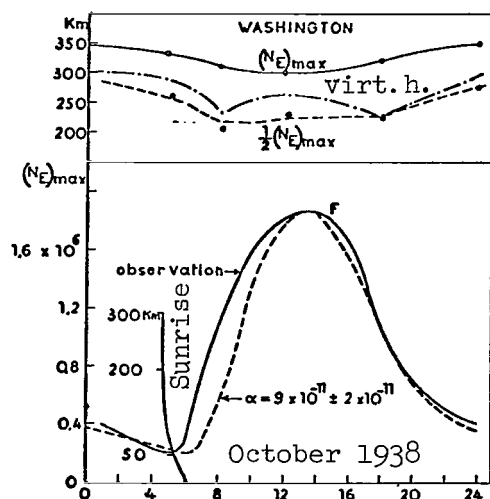
Figure 9. Values of the maximum electron concentration of the F_2 region and of its altitude at Washington in October 1938, according to F. L. Mohler, Jour. Res. Nat. Bur. Stand., 25, 507, 1940

$0.3 \cdot 10^{-10}$. However, these results do not, in any way, clarify the abnormal decrease about noon and, in the final analysis, provide only approximate data for the simplest variations.

Seasonal and Geographical Variations

Whereas in the Northern Hemisphere the electron concentration is at a minimum in summer and presents an annual variation similar to the diurnal variation, its behavior is completely different in the Southern Hemisphere. Despite numerous investigations (Ref. 36) undertaken in order to determine the various components of the global variation, the anomalies presented by the F_2 region have not yet been elucidated. Thus,

Appleton (Ref. 37) has determined (Figure 10) the characteristic variation of the ionization of the F_2 region for a period of solar activity

constant for two locations situated at $39°N$ and $39°S$ latitude, respectively. According to Figure 10, there is first an abnormal seasonal effect resulting from the existence of an ionization minimum in summer (June-July for $39°N$ and December-January for $39°S$). This phenomenon should be compared with the relative minimum at noon. It would, therefore, be necessary to study the simultaneous variation of the real
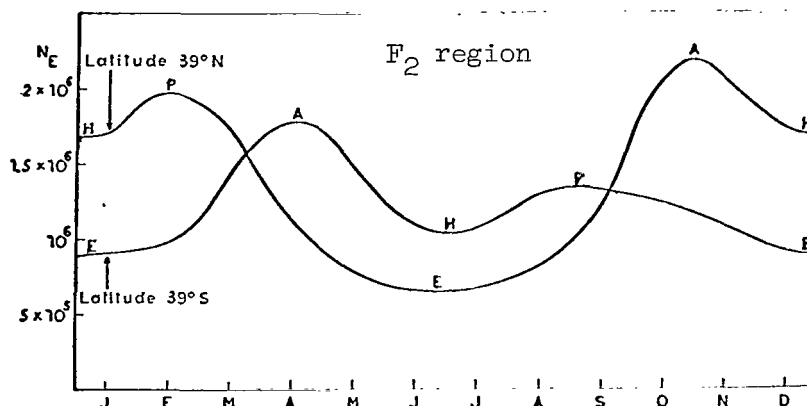
Figure 10. Characteristic variation of the noon elec-
tron concentration of the F_2 region for a constant
period of solar activity for two stations located at
the same latitudes in the two hemispheres.

The maxima P represent the spring maxima; the mini-
ma E, the summer minima; the maxima A, the autumn
maxima, and the minima H, the winter minima

height of the layer. Furthermore, the ionization minimum in winter at
the two stations may correspond to the normal decrease observed in all
the cases where the solar influence decreases. Finally, an appreciable
asymmetry (Figure 10) which could not be related to any known variation
exists between the annual curves in the two hemispheres.

From the general behavior of ionization in the F_2 region, it is

practically impossible to deduce simple variations analogous to those of
the lower regions, and it is therefore necessary to perform investiga-
tions along completely different lines. Because of the high altitude of
the F_2 region, the ratio of the molecular concentration to the electron

concentration is appreciably lower than the ratio corresponding to the
E region. Hence, it is possible that the earth's magnetic field may
play the most important part in the distribution of the ionization. A
recent report by O. Burkard (Ref. 38) seems to indicate that this line
of research could be fruitful. By considering the semestral ionization
averages supplied by the stations whose data are sufficient, it is found
that a linear relation between the maximum electron concentration and
the cosine of the geomagnetic latitude exists. Furthermore, it is ap-
parent from the same results that an effect of the geomagnetic longitude
exists on the date of the appearance of the annual maximum and minimum

of ionization. It appears, therefore, that the magnetic field causes a dissymmetry in the distribution of the ionization with respect to the normal geographical distribution. Furthermore, it may be noted that there is a definite correlation expressed by a linear relation between the geographical latitude and the average ionization. We can therefore assume, in the final analysis, that an examination of new observations of the F_2 region will have to be undertaken by considering the geograph-

ical and geomagnetic positions at the same time.

Long-Period Variation

Although it is practically impossible to determine the diurnal, seasonal and geographical components of the variation in the electron concentration of the F_2 region, the type of variation subject to the

solar activity appears more readily. It is even sufficient, without eliminating the other variations, to compare the average electron concentrations observed at a given station with the data which best represent the solar activity. Indeed, one finds that there is a good relationship between the two variations (Ref. 29). For the period from 1934 to 1937, which corresponds to a little less than a half-cycle of the 11-year solar activity, the average electron concentration at noon at Washington in

the F_2 region changed from $4.2 \cdot 10^5$ to $1.4 \cdot 10^6$ electrons per cm^3. During

the same period, the increase of the electron concentration in the E and F_1 regions is described by a factor (Ref. 39) of the order of 1.6.[1]

Similarly, if we compare the average values for the same month, for

example, $\dfrac{(N_E) \text{ July } 1937}{(N_E) \text{ July } 1934}$, we find the value of the ratio to be 1.51 for

the E region, 1.55 for the F_1 region, and 2.34 for the F_2 region.

For $\dfrac{(N_E) \text{ July } 1939}{(N_E) \text{ July } 1934}$, we have 1.4 for the E region, 1.3 for the F_1

region, and 1.71 for the F_2 region. Thus, as was noted by F. L. Mohler

(Ref. 35), we find that the factor of increase in the ionization of the F_2 region resulting from the solar activity is approximately equal to the square of the corresponding factor of the E and F_1 regions.

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[1] On the basis of the results of a study by Appleton and Naismith (Ref. 39), we have the following values for the ratios of the electron concentration at the maximum and minimum of solar activity: 1.50 for E and 1.58 for F_1.

If we compare the 11-year variation of the F_2 region with the various forms representing the solar activity, we find that the best correlation is given by the facular plages of ionized calcium (see Goodall, Ref. 40). However, this result merely indicates that the counting of the facular plages is done on an arbitrary scale which tends to smooth out the fluctuations of the facular activity in contrast to the scale which gives the Wolf relative numbers for sunspots. In all cases, it is possible to represent the effect of the solar activity in a simple form. Let $(N_E)_{max,M}$ be the maximum electron concentration of the region during a solar activity maximum and $(N_E)_{max,m}$ be the corresponding value during a minimum.

Let us set

$$\frac{(N_E)_{max,M}}{(N_E)_{max,m}} \equiv S \tag{I.8}$$

and, on the basis of the interpretation indicated above for the experimental results, we shall obtain the following relations which can be accepted to a first approximation:

$$S_E^2 \simeq S_{F_1}^2 = S_{F_2} \tag{I.9}$$

where the indices E, F_1 and F_2 designate the regions E, F_1 and F_2.

Nocturnal Variation

After sunset, the conditions of ionization are obviously less complex, and the various experimental investigations yield fairly consistent results. Thus, Appleton, by applying the law $\dfrac{\partial N_E}{\partial t} = -\alpha N_E^2$, has determined the following values of α for the southeast of England:

Period	Value of α	Period	Value of α
25-26 April 1933	3.7 to $6.0 \cdot 10^{-10}$	16-17 May 1934	$2.9 \cdot 10^{-10}$
11-12 April 1934	$3.6 \cdot 10^{-10}$	24-25 July 1934	$3.4 \cdot 10^{-10}$
April (av.) 1934	$2.5 \cdot 10^{-10}$	Sept. (av.) 1934	$1.84 \cdot 10^{-10}$

Similar determinations made by Mohler (Ref. 41) for the Washington station give an average value of $0.7 \cdot 10^{-10}$ for 20 months, distributed over the period 1937-1939. These individual values of the recombination coefficient α do not differ very much from one another and are all lower than those obtained by Appleton. This difference is due solely to the fact that the coefficients do not correspond to the same period. Indeed, similar determinations (Ref. 41) at Washington based on 10 months chosen during the 1934-1935 period yield values of α (as variable as those obtained by Appleton) between $2 \cdot 10^{-10}$ and $6 \cdot 10^{-10}$. Consequently, for the same period, the recombination coefficients α are identical at the two stations.

Thus, this dispersion in the values of the recombination coefficient α and its variation as a function of N_E (1934 to 1937) indicates that α depends on the value of the electron concentration. In other words, one should write (see Note in Section 3, page 20):

$$\frac{\partial N_E}{\partial t} = - \alpha N_E^2 - \beta N_E \qquad (I.10)$$

This relation, applied to the nocturnal variation of N_E in the case studied by Mohler for June-July 1938 (Figure 8) yields

$$\frac{\partial N_E}{\partial t} = - 0.3 \times 10^{-10} N_E^2 - 2 \times 10^{-5} N_E \qquad (I.11)$$

This result applies to an average altitude of 360 km, corresponding to the maximum of the electron concentration. On the basis of the knowledge of the variation at a lower altitude (270 km), Mohler (Ref. 41) was also able to study the nocturnal variation and obtained

$$\frac{\partial N_E}{\partial t} = - 17 \times 10^{-5} N_E \qquad (I.12)$$

which demonstrates the increase of an equivalent recombination coefficient with the increase in molecular concentration.

In short, the nocturnal electronic variation of the F_2 region follows a law different from that of the E region. The remarkable constancy of the effective recombination coefficient in the E region contrasts in the F_2 region with a variation law that depends directly on the electron and molecular concentration.

Variation During Eclipses

Observation of the variation of ionization in various regions of the ionosphere during eclipses should provide the indisputable criterion of the electromagnetic or corpuscular nature of the solar radiation causing the ionization. Whereas, in the case of the E and F_1 regions, there exists a perfect simultaneity between the electron variations and the eclipse of an electromagnetic radiation, the results obtained for the F_2 region do not quite agree (Ref. 31).

Despite the rapidity of the effect of the sun at sunrise, the corpuscular origin of the ionization has always been considered possible by various authors. However, recent determinations made in Brazil (Ref. 33) and South Africa (Ref. 42) during the eclipse of 1 October 1940 have finally supplied an experimental confirmation of the fact that the F_2 region is subjected to solar ultraviolet radiation. Thus far, we do not have all the details of the observations, but we can deduce from the information obtained (Ref. 42) that the instants of minimum electron concentration appear, respectively, 30 minutes and one hour following totality in South Africa and Brazil. Whereas in Brazil the decrease in ionization up to the end of totality corresponds to a recombination coefficient $\alpha = 10^{-10}$, the ionization observed after the eclipse is less than the value which should be expected for $\alpha = 10^{-10}$. On the other hand, in South Africa, the observed variation corresponds to a decrease of about 25 percent and the observed α coefficient would be of the order of $4 \cdot 10^{-11}$. Finally, the search for a corpuscular effect has shown that the latter did not take place.

In summary, the observations performed during eclipses reveal that the electron production of the F_2 layer is not in equilibrium with the recombination. The low relative value of the equivalent recombination coefficient α as well as the differences observed in the course of the same eclipse prove satisfactorily that the laws of the electronic variation are strongly dependent on the physical conditions of the upper atmosphere.

Perturbations

While the normal conditions characterizing the F_2 layer are ill-defined, various perturbations such as sporadic fluctuations and

ionospheric storms admit of only pictorial descriptions. While awaiting data on the fine structure of the ionization state, we shall confine ourselves to the general considerations which have already been indicated in the case of the E layer.

In conclusion, the results acquired by observations of the F_2 region indicate that the electron concentration is subjected to the effect of electromagnetic solar radiation. However, the low value of the recombination coefficient shows that the layer undergoes fluctuations which depend mainly on the physical conditions of the atmosphere at high altitudes.

Section 6. Sudden Fade-Out

During the development of an eruption within a facular solar plage, a magnetic perturbation whose maximum intensity is observed when the sun is at the zenith appears simultaneously with a sudden fade-out of short waves and with a reinforcement of long waves. An ionospheric study has shown primarily that the F_2 region suffers only slight modifications

(Ref. 43) due to the solar eruption. Indeed, it can be shown that after the fade-out has ceased, this region preserves the same structure as before. Moreover, since the normal behavior of the ionization makes it possible to show that the recombination coefficient is no greater than

10^{-10}, it is certain that if important modifications were involved in the structure of the F_2 region, they would necessarily be observed. As

far as the E layer is concerned, where the recombination coefficient is

greater than 10^{-8}, the fade-out effect may disappear a short time after the fade-out has ceased, for the layer returns rapidly to its equilibrium state. L. V. Berkner (Ref. 43) has shown that the E region reappears with a slight increase in the electron concentration. Thus, since the absorption is sure to take place below the maximum electron concentration, it may be concluded that the fade-out results from an increase in the ionization at the base or below the E layer, i.e., at an altitude of less than 100 km.

Sudden short wave fade-outs are reflected in recordings of atmospherics. R. Bureau (Ref. 44) has shown that a sudden reinforcement of long waves is shown by the recording of atmospheric noise. On the other hand, Budden, Ratcliffe and Wilkes (Ref. 28), by studying the propagation of long waves of 18.8 km, fixed the average altitude of the "reflection" level at 67 km. In summary, the ionospheric observations show

that the ionospheric perturbation with a sudden commencement is localized between 65 and 100 km.

The magnetic effects associated with solar eruptions show well-defined characteristic properties. Mc Nish (Ref. 45) has shown the similarity of the respective changes in the earth's magnetic field during the normal diurnal variation and in the considered perturbation. Indeed, for a given station and hour, the perturbation is manifested by a modification of the earth's magnetic field similar in magnitude and direction to that of the normal diurnal variation. In other words, the chromospheric eruption produces an ionospheric perturbation and hence an associated magnetic perturbation whose essential feature is an increase of the normal diurnal variation of the earth's magnetic field. Such an effect coupled with the ionospheric results indicates therefore that the normal magnetic diurnal variation results from a current of charged particles in a region situated between 65 and 100 km, and that the magnetic perturbations corresponding to sudden ionospheric perturbations arise in the same region of the upper atmosphere.

Since our purpose is to determine the physical conditions which take into account all of these various properties, we have to consider the nature of the association which exists between the fade-outs and the eruptions. A quantitative study has not yet been made, but a statistical investigation by Giovanelli and Higgs (Ref. 46) during the 1937-1938 period corresponding to the solar activity maximum makes it possible to draw certain conclusions. The appearance of a sudden fade-out depends both on the intensity and on the surface covered by the eruption. Although it is not yet possible to determine the relation existing between the values of the surface area and the intensity, it appears nevertheless that the product of these two variables must exceed a certain limit. Furthermore, for an intensity of the H_α line of hydrogen lower than that

of the neighboring continuous spectrum, an eruption produces a fade-out only in exceptional cases. Finally, because of the influence of the optical thickness traversed by the solar rays, the height of the sun above the horizon must reach a minimum value of 15° to make a sudden fade-out of short waves observable.

CHAPTER II. SOLAR RADIATION

Section 1. Introduction

That solar radiation plays an effective part in the formation of
the ionosphere is proven directly by daily observations of the varia-
tion in the ionization of the upper atmosphere. Furthermore, there is
no doubt whatsoever about the nature of this radiation, for observations
during solar eclipses have revealed that the ionizing agent propagates
at the speed of light. In addition, since the atoms and molecules in
the upper atmosphere have relatively high ionization potentials, it fol-
lows that the solar energy absorbed in the process of ionization corre-
sponds to the invisible ultraviolet region of the spectrum. Thus, the
first problem to be solved in determining the physical properties of the
ionosphere is to investigate the fundamental characteristics of this
radiation. In other words, it is necessary to determine the solar energy
usable for the ionization of the upper atmosphere by taking into account
the results of observations and the theoretical conclusions. Thus far,
the application has been confined to the determination of a simple emis-
sion of a black body whose temperature is of the order of 6,000°K.[1]
However, this concept is excessively simple, and we shall show that it
is necessary to consider the complete structure of the solar atmosphere
in order to deduce the actual source of the effective radiation.

In accordance with the means of investigation employed (Ref. 47),
the solar atmosphere shows us the various layers which comprise it.
Visual or photographic observation shows us the photosphere with its
granulation, which produces the total radiation determined by the solar
constant. Hence, by applying the Stefan-Boltzmann law relative to the
total radiation emitted by a black body, it can be deduced that the ef-
fective temperature of the sun is of the order of 5,740°K. However,
even if this temperature accounts for the total energy radiated by the
sun in the observable region, is it still adequate for the invisible ul-
traviolet region? On the affirmative side, it is implicitly assumed
that in the extreme portions of the spectrum, the sun follows the laws

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[1]F. L. Mohler (Science, Vol. 90, 137, 1939) has suggested the effect of
flocculi, which should be at a temperature of 7,500°K, on the production
of ionization of the F_2 layer.

of radiation of a black body at the fixed temperature of 5,740°K. This is inadmissible, since this effective temperature differs from the temperatures given by the laws of Wien or Planck. Indeed, the maximum intensity of the spectrum gives a temperature of the order of 7,000°K. Moreover, a comparison of the energy distribution in the solar spectrum with the distribution corresponding to Planck's law indicates different temperatures in the different spectral regions. In the final analysis, all these temperatures have only a limited meaning, and some agreement should be reached concerning the concept of "temperature". It is obvious that we cannot consider a temperature deduced from the application of black-body laws to the sun to be a thermodynamic temperature. We shall therefore assume an "equivalent temperature", which will make it possible to account for the spectral properties of the radiation emitted in the invisible ultraviolet by application of Planck's law.

Above the photosphere which emits the continuous spectrum, a spectroscopic observation shows us the reversing layer, which produces absorption lines. This layer is therefore at a temperature lower than that of the photosphere. Determinations indicate that the limiting temperature at the upper part of the layer is of the order of 4,840°K.

Spectroheliographic and spectroscopic observations during eclipses show the presence of a layer which is concentric with the reversing layer, the chromosphere, which is characterized by the emission of noticeable radiations such as the lines of hydrogen and helium. Finally, the last layer, the corona, emits forbidden radiations of strongly ionized elements.

Hence, if use is made of the results acquired by observation of the layers of the solar atmosphere, no distinct picture of the ultraviolet emission is directly obtained. However, as far as the continuous emission is concerned, it is necessary to retain the possibility of radiation from a black body at various equivalent temperatures. In the case of the monochromatic emission, the chromospheric radiations cannot be neglected a priori, particularly since the facular plages correspond to an excess of these radiations in comparison to the normal chromosphere. In addition, since the number of facular plages is a function of the general activity of the sun, the monochromatic chromospheric emission should be related to the general solar activity.

In summary, the solar radiation, which may determine the ionization in the upper atmosphere, can only originate from the continuous photospheric radiation which has traversed the various layers of the solar atmosphere, and from the nonreabsorbed ultraviolet chromospheric radiation.

Section 2. Radiation of the Continuous Spectrum

In determining the ultraviolet energy which reaches the top of the atmosphere, an approximate representation has always been adopted. The sun is considered to be a black body with an absolute temperature T_s.

Such a schematization permits one to calculate the emitted energy by the application of Planck's law.

Let $\varrho_s(v)$ be the radiation density (of frequency v) of the sun considered as a black body. At the top of the atmosphere, the density of this radiation is reduced by the dilution factor $\beta_s = R^2/4r^2 = 5.4 \cdot 10^{-6}$ (R is the radius of the spherical source = radius of the sun, and r is the distance of the point considered to be at the source = distance from earth to sun). Hence, using Planck's law,

$$\beta_s \varrho_s(v) = \frac{8\pi h \beta_s v^2}{c^3} \left(e^{hv/kT_s} - 1 \right)^{-1} \tag{II.1}$$

represents the density of the solar radiation of frequency v at the top of the atmosphere. In this relation, the symbols[1] have the usual meaning: h = $6.62 \cdot 10^{-27}$, Planck's constant; k = $1.379 \cdot 10^{-16}$, Boltzmann's constant; c is the speed of light and T_s is the sun's temperature.

The energy of a quantum of frequency v being hv, the number of quanta emitted per second per cm^2 and reaching the top of the atmosphere is given by

$$Q = \beta_s \int_{v_1}^{v_2} \frac{c\varrho_s(v)}{hv} \, dv = \frac{8\pi\beta_s}{c^2} \int_{v_1}^{v_2} v^2 \left(e^{hv/kT_s} - 1 \right)^{-1} \, dv \tag{II.2}$$

where v_2 and v_1 represent the two frequency limits between which we are considering the emission. The integrated relation (II.2) is then written in a simplified form used for numerical calculations,

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[1] The unit system employed in this work is the CGS system.

$$Q = \frac{8\pi\beta_s}{c^2}\left(\frac{k}{h}\right)^3 T_s^3 \left\{ e^{h\nu/kT_s}\left[\left(\frac{h\nu}{kT_s}+1\right)^2 + 1\right]\right\}_{\nu_2}^{\nu_1} \qquad (II.3)$$

if we assume that $e^{h\nu/kT_s}$ is appreciably greater than 1. This case holds for the entire unobservable ultraviolet region.[1]

Thanks to expression (II.3), we have deduced the number of quanta usable at the top of the atmosphere for certain spectral regions. For $T_s = 6,000°K$, $5,740°K$ and $5,000°K$, the results are collected in Table 1.

The selected frequency limits may seem arbitrary at first sight; in fact, they correspond to certain regions which are immediately applicable to the photoionization of the compounds found in the atmosphere. In Figure 11,

Table 1. Number of quanta usable at the top of the atmosphere
for various temperatures of the black body

Spectral region		T = 6,000°	T = 5,740°	T = 5,000°
ν to ∞	λ to o			
ν/c in cm^{-1} 17,830	in Å 5,606	$1.2\cdot10^{17}$	$9.2\cdot10^{16}$	
41,450	2,412	$1.6\cdot10^{15}$	$1.0\cdot10^{15}$	$1.6\cdot10^{14}$
57,100	1,750	$7.2\cdot10^{13}$	$3.7\cdot10^{13}$	$3.5\cdot10^{12}$
77,000	1,300	$1.1\cdot10^{12}$	$4.3\cdot10^{11}$	$2.2\cdot10^{10}$
100,000	1,000	$7.0\cdot10^{9}$	$1.8\cdot10^{9}$	$4.8\cdot10^{7}$
109,670	910	$7.9\cdot10^{8}$	$2.5\cdot10^{8}$	$3.6\cdot10^{6}$
117,670	850	$1.3\cdot10^{8}$	$3.8\cdot10^{7}$	$4.1\cdot10^{5}$
125,670	795	$2.2\cdot10^{7}$	$5.9\cdot10^{6}$	$4.65\cdot10^{4}$
151,300	661	$6.5\cdot10^{4}$	$1.4\cdot10^{4}$	$3.3\cdot10^{0}$
198,300	504	$1.4\cdot10^{0}$	$1.8\cdot10^{-1}$	$9.5\cdot10^{-5}$

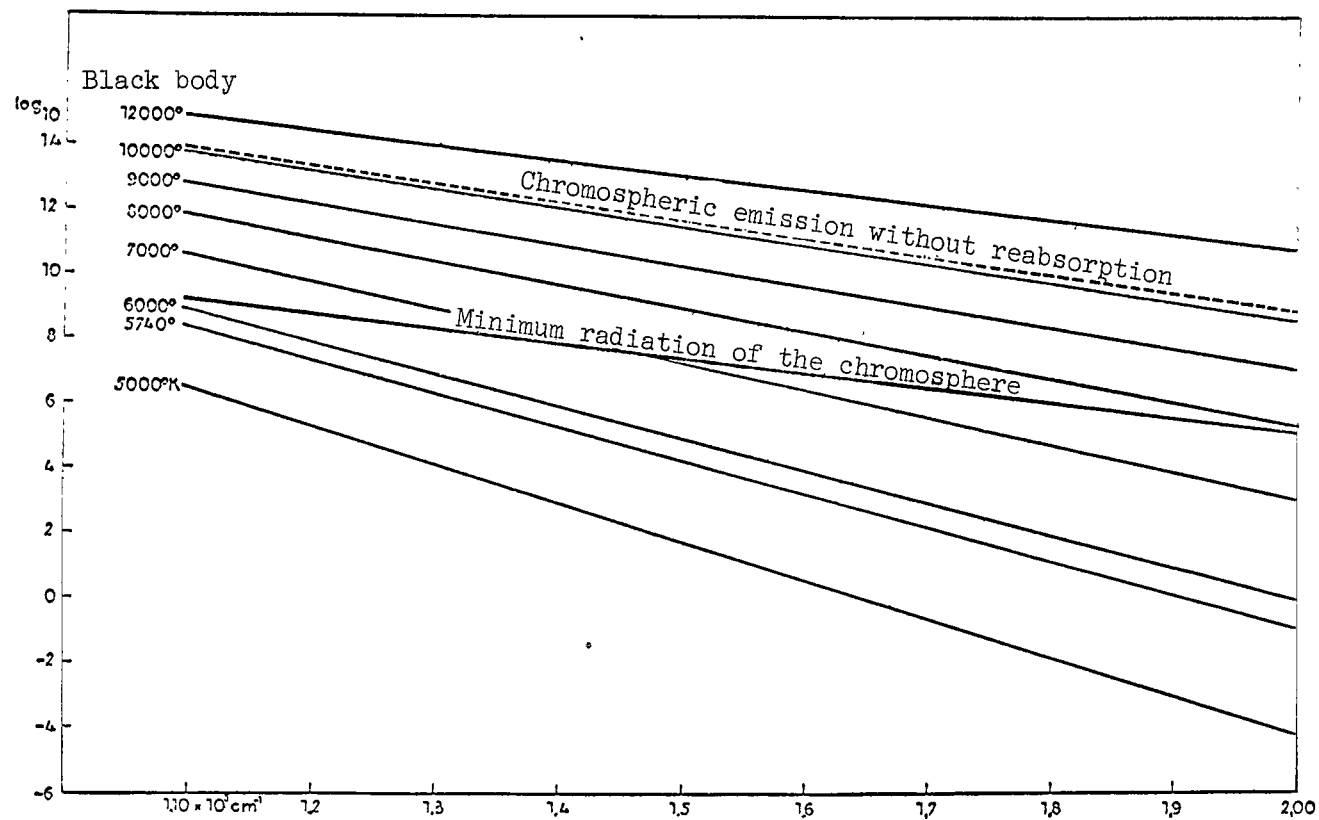[1]If 1 is not negligible compared to e^{-x}, it is sufficient to write $x^2 e^{-x}(1 + e^{-x} + e^{-2x} + ...)\,dx$.

Figure 11

Abscissas: number of waves in cm^{-1}.
Ordinates: number of quanta from ν/c to ∞ reaching the top of the earth's atmosphere.

a graphical representation is given of the results obtained with the aid

of (II.3) for λ 910 $\overset{o}{A}$ and $5,000^{o}K \leqslant T_s \leqslant 12,000^{o}K$. This representation

will permit a comparison with the results obtained by a study of the
chromospheric emission.

The first conclusion which may be drawn from Table 1 is a rapid de-
crease in the number of quanta at the ultraviolet end of the spectrum
when the temperature decreases. One can thus understand the general
tendency to use elevated temperatures for the explanation of geophysical
phenomena necessitating an abundant ultraviolet energy. However, it is
impossible to assume in all cases an excess of far ultraviolet with
respect to a black body at $5,000^{o}K$. Indeed, we know from a quantitative
analysis of the solar atmosphere that atomic hydrogen is the most abun-
dant constituent. This atom, whose ionization potential is equal to
12.53 ev, has a continuum whose absorption coefficient is equal to

$6.6 \cdot 10^{-18} \, v_0^3 \, v^{-3}$, where v_0 denotes the ionization frequency. Calcula-

tion shows that the major part of the photospheric radiation of wave-

lengths below 910 $\overset{o}{A}$ is absorbed, and that the continuous energy emitted
by the photosphere cannot escape from the solar atmosphere. The origin

of ultraviolet radiation with wavelengths of less than 910 $\overset{o}{A}$ should,
therefore, be sought in the chromosphere.

Section 3. Chromospheric Radiation

The chromospheric emission in the observable spectral region is
characterized by intense radiations, among others those of hydrogen and
helium, which are immediately followed by transitions corresponding to
radiations in the far ultraviolet. The emission of lines of the Balmer
series of hydrogen is associated with the emission of lines of the
Lyman series, which correspond to transitions from the normal state.
Under the same conditions, neutral helium HeI emits radiations of very

short wavelengths which form a series whose first line is λ 584 $\overset{o}{A}$;
ionized helium HeII also presents lines of a fundamental series whose

wavelengths are less than 303.7 $\overset{o}{A}$. A radiation at λ 1,640.5 $\overset{o}{A}$ is emitted
immediately after the observable radiations of HeII.

In addition to this emission of monochromatic radiations, the pre-
sence of the Balmer series continuum is also observed. Such a continuous

spectrum, which is due to the radiative recombination of electrons and positive hydrogen ions in the second quantum state, is analogous to an invisible continuum at the limit of the Lyman series.

No data are available at present on this chromospheric emission in the far ultraviolet. However, a determination of the quanta usable at the top of the atmosphere should allow a comparison with the continuous emission of black bodies at various temperatures. To this end, we shall investigate the energy emitted by the solar atmosphere by means of measurements of the intensities of observed chromospheric radiations. The results obtained by Menzel and Cillié (Ref. 48) constitute a body of data which will serve as the basis for our determination.

In measuring the chromospheric radiation intensities obtained during solar eclipses, we consider the energy radiated by a slice of the chromosphere. This slice (see Figure 12) corresponds to a volume bounded by a plane A tangent to the edge of the moon and by two parallel planes B and C which are perpendicular to plane A. These various planes are located in the direction of the observer. Plane A is located at a height x above the face of the chromosphere and planes B and C are placed at a distance of 1 cm, in order to define a chromospheric slice (1 cm thick) located at a height x above the base of the chromosphere.

The chromospheric slice thus defined may be divided into columns 1 cm^2 in cross section. Such a transverse column is, therefore, a paral-lelepiped whose section is equal to 1 cm^2, and which traverses the chromosphere from one end to the other at a fixed height above the base of the chromosphere. However, what we are interested in is not the radiation emerging from a transverse column but the radiation emerging from a radial column with a cross section of 1 cm^2.

To determine the relation which gives the ratio of the emerging radiations of the transverse and radial columns, it will suffice to consider the energy emitted within these columns. If E_t and E_r are the radiative energies emitted within the transverse and radial columns, and N_t and N_r are the respective numbers of emitting atoms within these columns, we can write

$$\frac{E_t}{E_r} = \frac{N_t}{N_r} \qquad \text{(II.4)}$$

Edge of the chromosphere

Base of the chromosphere

A

Chromospheric slice

R

B

C

Observer perpendicular to figure

Edge of the sun

Edge of the moon
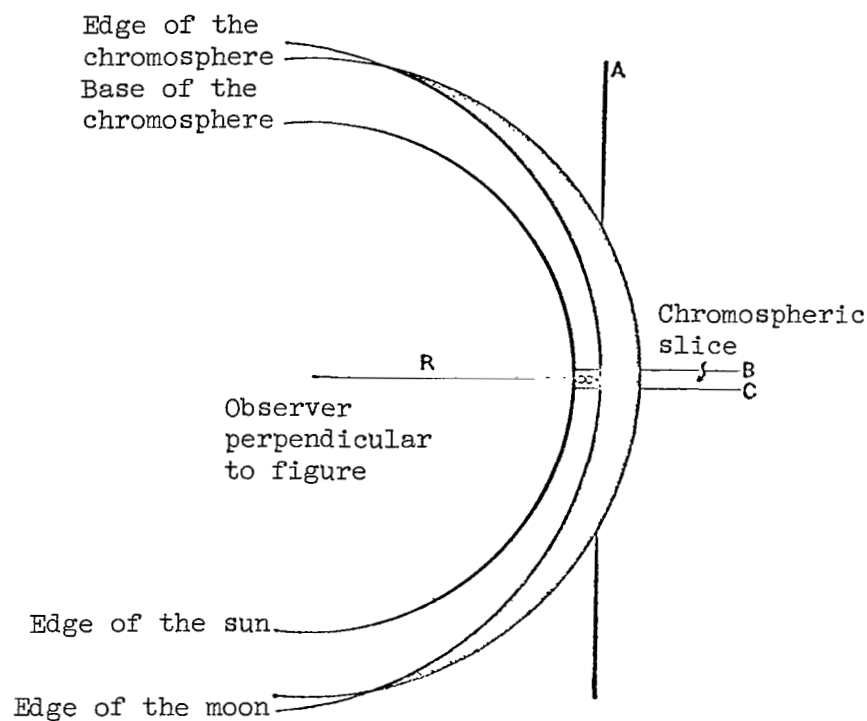
Figure 12

In order to determine the values of N_t and N_r, let N be the atomic concentration at altitude z above the base of the chromosphere. In the case of an exponential distribution of the constituents, we have

$$N = N_0 \, e^{-\theta z} \qquad\qquad (II.5)$$

where θ is the logarithmic parameter of the distribution and N_0 is the number of atoms at level $z = 0$.

From (II.5), it follows that the number of atoms in a radial column whose base is located at a height x_1 is

$$N_r = \int_{x_1}^{\infty} N \, dz = N_0 \int_{x_1}^{\infty} e^{-\theta z} \, dz = \frac{N_0}{\theta} e^{-\theta x_1} \qquad\qquad (II.6)$$

On the other hand, the total number of atoms of a transverse column located at altitude x above the base of the chromosphere is equal to (see Figure 13)

$$N_t = \int_{-\infty}^{+\infty} N(z)\,dy \qquad (II.7)$$

where y is given by the relation (R being the solar radius):

$$y^2 = (R + z)^2 - (R + x)^2 \qquad (II.8)$$

Since z and x are negligible compared to R, we can write to an excellent approximation

$$z = x + \frac{y^2}{2R} \qquad (II.9)$$

Based on (II.9), expression (II.7) is written as

$$N_t = 2N_o \int_0^\infty e^{-\theta z}\,dy = 2\int_0^\infty N_o e^{-\theta(x + \frac{y^2}{2R})}\,dy = \sqrt{\frac{2\pi R}{\theta}}\,N_o e^{-\theta x} \qquad (II.10)$$

Finally, taking into account (II.6 and 10) where $x = x_1$, relation (II.4) is written as

$$\frac{E_t}{E_r} = (2\pi\theta R)^{1/2} \qquad (II.11)$$

This relation thus gives the ratio of the energies emitted within the transverse and radial columns. This ratio corresponds to the ratio of the intensities of a radiation emerging from the transverse and radial columns when the reabsorption is negligible.

A. Chromospheric Emission in the Continuum at the Limit of the Lyman Series of Hydrogen

On the basis of the values of the intensities observed in the various regions of the continuum of the Balmer series $(\lambda < 3,640\ \text{Å})$, we shall deduce the distribution of the energy emitted within the chromosphere for the ultraviolet spectral region corresponding to the continuum
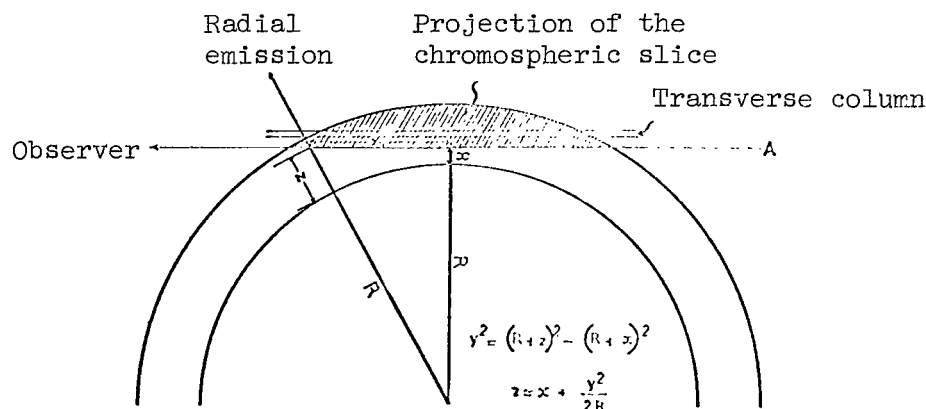
Figure 13

The plane of this figure is $/\!/$ to the planes B and C shown in Figure 12

of the Lyman series ($\lambda < 910$ Å). Next, we shall determine the reabsorption within the chromosphere in order to calculate the energy escaping the solar atmosphere.

Menzel and Cillié (Ref. 48) have furnished the values of the chromospheric emission at various wavelengths of the Balmer series continuum. They thus obtained the energy radiated per slice of the chromosphere in a certain frequency interval for the solid angle 4π. Thanks to the results obtained during the solar eclipse of 1932, one finds that the energy radiated at the head of the Balmer series continuum in a complete solid angle for an interval $\frac{dv}{c} = 1$ cm^{-1} is equal to $3.24 \cdot 10^{11}$ erg per second. This energy corresponds to the radiation emerging from a chromospheric slice of 1 cm^2 cross section, when the edge of the moon is 1,500 km beyond the edge of the sun. Menzel and Cillié hold that this region represents the global chromospheric emission (in 1932, during the solar activity minimum).

Hence, if we neglect the reabsorption effect, the energy emerging from a radial column $(E_{CBa})_{v=v_0}$ for an interval $\frac{dv}{c} = 1$ cm^{-1} will therefore be equal to

$$(E_{CBa})_{v=v_0} = 3.24 \cdot 10^{11} \cdot 1.54 \cdot 10^{-8} = 4.99 \cdot 10^3 \text{ erg sec}^{-1}\text{cm}^{-2} \quad \text{(II.12)}$$

where $\theta = 1.54 \cdot 10^{-8}$ cm^{-1}. The indices C and Ba indicate that we are dealing with a continuum of the Balmer series.

These $4.99 \cdot 10^3$ ergs result, therefore, from the emission of a continuum $\dfrac{dv}{c} = 1$ cm^{-1} which corresponds to the radiative recombination of positive hydrogen ions and electrons. It is readily shown (see formula (IV.41)) that for a given electronic temperature T_E^S, the energy distribution $E_c dv$ within a continuum is given by

$$E_c dv = C_1 N^+ N_E \frac{g_n}{g_c} T_{SE}^{-3/2} \varkappa(v) v^3 e^{-h(v - v_0)/kT_{SE}} dv \tag{II.13}$$

where C_1 is a constant, $N^+ N_E$ is the product of the numbers of positive ions and electrons, h and k are Planck's and Boltzmann's constants, v_0 is the ionization frequency, g_n and g_c are, respectively, the statistical weights of the quantum state n and of the ionized state, $\varkappa(v)$ is the absorption coefficient, $T_{SE} = 12,000^\circ$K according to the observations of Menzel and Cillié (Ref. 48), and where $v > v_0$.

In the case of hydrogen, the absorption coefficient $\varkappa(v)$ is given by

$$\varkappa(v) = C_2 \frac{v^{-3}}{n^5} = \varkappa(v_0) v_0^3 v^{-3} \tag{II.14}$$

where C_2 is a constant and n is the principal quantum number.

Using (II.14), equation (II.13) may be applied to hydrogen and, since $g_n = n^2$, $g_c = 1$, may be written as

$$E_c dv = C_3 N^+ N_E T_{SE}^{-3/2} e^{-h(v - v_0)/kT_E} \frac{dv}{n^3} \tag{II.15}$$

where C_3 is a new constant.

For the Lyman series, n = 1, and for the Balmer series, n = 2; hence, (II.15) makes it possible to write, $v - v_0$ being identical for

the two continua, that the ratio E_{CLy}/E_{CBa} of the energy distributions is equal to

$$\frac{E_{CLy}}{E_{CBa}} = 8 \qquad (II.16)$$

From (II.12 and 16), we find that the total emission within a radial chromospheric column at the head of the continuum of the Lyman series and for an interval $\frac{dv}{c} = 1$ cm^{-1} is given by

$$(E_{CLy})_{v=v_0} = 4.99 \cdot 10^3 \cdot 8 = 3.99 \cdot 10^4 \text{ erg sec}^{-1}\text{cm}^{-2} \qquad (II.17)$$

Finally, by virtue of (II.15 and 17), the energy distribution in the continuum will be given by

$$E_{CLy}\, dv = \frac{3.99 \times 10^4}{c} \times 1.315 \times 10^6 \times T_{SE}^{-3/2} e^{-h(v - v_o)/kT_{SE}}\, dv \qquad (II.18)$$

and the number of quanta $Q(v)$ by

$$Q(v)dv = \frac{5.25 \times 10^{10}}{ch} T_{SE}^{-3/2}\, e^{-h(v - v_o)/kT_{SE}}\frac{dv}{v} \qquad (II.19)$$

The numerical factor $5.25 \cdot 10^{10}$ involved in this last expression is, in the final analysis, provided by observation. It is a function of the product N^+N_E, which depends on the ionization conditions in the chromosphere.

In a fixed spectral range, v_1 to ∞, the number of quanta of the Lyman continuum emitted within a radial column of the chromosphere is obtained by integrating expression (II.19),

$$\int_{v_1}^{\infty} Q(v)dv = \frac{5.25 \times 10^{10}\, T_{SE}^{-3/2} e^{h v_0/kT_{SE}}}{ch} \int_{v_1}^{\infty} \frac{e^{-hv/kT_{SE}}}{v}\, dv \qquad (II.20)$$

By setting $\frac{hv}{T^{SE}} = x$ and

$$\mathrm{Ei}\left(\frac{h\nu_0}{kT_{SE}}\right) \equiv \int_{h\nu_0/kT_{SE}}^{\infty} \frac{e^{-x}}{x}\,dx \qquad (II.21)$$

(II.20) may be written as

$$\int_{\nu_1}^{\infty} Q(\nu)d\nu = \frac{5.25 \times 10^{10}}{ch} T_{SE}^{-3/2} e^{h\nu_0/kT_{SE}} \mathrm{Ei}\left(\frac{h\nu_1}{kT_{SE}}\right) \qquad (II.22)$$

Consequently, the number of quanta corresponding to $\lambda < 910$ Å emitted within a radial column of the chromosphere is determined by a relation such as (II.22) when the electronic temperature is known.

The distribution parameter θ of hydrogen, which is equal to $1.54 \cdot 10^{-8} \mathrm{cm}^{-1}$, corresponds to the distribution parameter of the quantum emission of the Lyman series continuum. Indeed, the value of the recombination (giving the quanta of the Lyman series continuum) is proportional to the product of the number of positive ions and electrons. Since the ionization state in the chromosphere depends on the ionization of the main constituent, hydrogen, the vertical distribution of the number of quanta emitted follows the law

$$q(\nu) = q_0(\nu)\, e^{-\theta z} \qquad (II.23)$$

where $\theta = 1.54 \cdot 10^{-8} \mathrm{cm}^{-1}$, $q_0(\nu)$ is the number of quanta of frequency ν

emitted at the base of the chromosphere, and $q(\nu)$ is the number of quanta for frequency ν emitted at altitude z.

By integrating the two terms of (II.23) between the limits $z = 0$ and $z = \infty$, we obtain the number of quanta of frequency ν emitted within a radial column

$$Q(\nu) = \int_0^{\infty} q_0(\nu)\, e^{-\theta z}\, dz = \frac{q_0(\nu)}{\theta} \qquad (II.24)$$

Although the formulas (II.22, 23 and 24) provide complete data on the number and distribution of the quanta emitted within the chromosphere, it is nevertheless true that these quanta cannot all escape the solar atmosphere. Owing to the effect of reabsorption of hydrogen, the

quanta CLy (Lyman series continuum) undergo a degradation (cf. the Zanstra theory of nebulae), since they can be reemitted in the Balmer series, Paschen series, and finally, by L_α, the first line of the

Lyman series. Let us calculate this effect by using the working hypothesis that the degradation is complete.

Let $q_1(v)$ be the number of quanta of frequency v emerging from the chromosphere when the emission takes place within a radial chromospheric column located between altitude z and the outer edge of the chromosphere. We can then write

$$q_1(v) = q(v) \, e^{-\tau(v)} = q(v) \, e^{-\int_z^\infty N(H)\varkappa(v)\,dz} \qquad (II.25)$$

where $\tau(v)$ is defined by

$$d\tau(v) = \varkappa(v)N(H)dz \qquad (II.27)$$

$\varkappa(v)$ being the absorption coefficient and $N(H)$ the concentration of neutral hydrogen atoms.

Taking into account the vertical distribution of hydrogen and that of the number of emitted quanta (II.23), (II.25) may be written in the form

$$q_1(v) = q_0(v) \, e^{-0z} \, e^{-\varkappa(v) N_0(H) \int_z^\infty e^{-0z}\,dz} \qquad (II.28)$$

Then, by integrating (II.28) between the limits $z = 0$ and $z = \infty$, we obtain the total number of quanta $Q_1(v)$ emerging from the chromosphere, namely:

$$Q_1(v) = \int_0^\infty q_1(v)\,dz = q_0(v) \int_0^\infty e^{-0z} \, e^{-\varkappa(v) N_0(H) \int_z^\infty e^{-0z}\,dz}\,dz \qquad (II.29)$$

After performing the integrations, we get the formula

$$Q_1(v) = \frac{q_0(v)}{N_0(H)\varkappa(v)} \left[1 - e^{-\frac{\varkappa(v) N_0(H)}{0}} \right] \qquad (II.30)$$

which gives the number of quanta of frequency v emerging from a radial column of the chromosphere with the assumption that the reabsorption definitely degrades the quanta emitted in the Lyman series continuum

into quanta of the first line of the series, L_α ($\lambda = 1,215.7$ Å).

In order to apply (II.30), it is necessary to know the value of the absorption coefficient of hydrogen; knowing the constant C_2, we deduce from (II.24) that in the Lyman continuum,

$$\varkappa(v) = 6.66 \cdot 10^{-18} \, v_0^3 v^{-3} \tag{II.31}$$

In addition, it is necessary to know the hydrogen concentration. We obtain its value as follows: Menzel and Cillie (Ref. 48) have determined the number of atoms of ionized calcium $N_0(Ca^+)$ at the base of

the chromosphere to be $2 \cdot 10^8$ per cm^3; from the results of Strömgren (Ref. 49) we deduce that the ratio of the abundances of hydrogen atoms

to calcium atoms is equal to $6.15 \cdot 10^5$. Hence, by assuming that the calcium is practically ionized once, the number $N_0(H)$ of hydrogen atoms

per cm^3 at the base of the chromosphere is equal to $1.23 \cdot 10^{14}$.

By substituting the numerical values in relation (II.30), we see that

$$e^{-\frac{\varkappa(v)N_0(\mathrm{II})}{0}} = e^{-\frac{6.6 \times 10^{-18} \times 1.23 \times 10^{14}}{1.54 \times 10^{-8}}} = e^{-5.4 \times 10^4} \tag{II.32}$$

and hence that

$$\left[1 - e^{-\frac{\varkappa(v)N_0(\mathrm{II})}{0}}\right] \backsimeq 1 \tag{II.33}$$

Using (II.33), we can write (II.30), to an excellent approximation, in the following manner

$$Q_1(v)dv = \frac{q_0(v)dv}{N_0(\mathrm{II})\varkappa(v)} \tag{II.34}$$

whence, taking (II.31) and (II.24 and 19) into account,

$$Q_1(v)dv = \frac{5.25 \times 10^{10} \ 0 \ T_{SE}^{-3/2}}{ch N_o(II)\varkappa(v_o)v_o^3} \ v^2 e^{\ -h(v-v_o)/kT_{SE}} dv \qquad (II.35)$$

The total number of quanta of frequencies comprised between v_1 and ∞ escaping from the chromosphere is obtained by integrating (II.35)

$$\int_{v_1}^{\infty} Q_1(v)dv = \frac{5.25 \times 10^{10} \ T_{SE}^{-3/2} \ 0 \ e^{hv_o/kT_{SE}}}{ch \ N_o(II)\varkappa(v_o)v_o^3} \ \cdots \int_{v_1}^{\infty} v^2 e^{\ -hv/kT_{SE}} \ dv \qquad (II.36)$$

whence

$$\int_{v_1}^{\infty} Q_1(v)dv = \frac{5.25 \times 10^{10} \ 0 \ k^3 T_{SE}^{-3/2} \ e^{hv_o/kT_{SE}}}{ch^4 N_o(II)\varkappa(v_o)v_o^3 \ e^{hv_1/kT_{SE}}} \ \left[\left(\frac{hv_1}{kT_{SE}} + 1 \right)^2 + 1 \right] \qquad (II.37)$$

When the constants are replaced by their numerical values, (II.37) may be written as

$$\int_{v_1}^{\infty} Q_1(v)dv = 1.27 \times 10^6 \ T_{SE}^{3/2} \ e^{\ -h(v_1-v_o)/kT_{SE}} \left[\left(\frac{hv_1}{kT_{SE}} + 1 \right)^2 + 1 \right] \qquad (II.38)$$

The number of quanta (with frequencies comprised between v_1 and ∞) which reaches the top of the atmosphere per second per cm^2 is then given by

$$Q = \beta_s \int_{v_1}^{\infty} Q_1(v)dv = 6.84 \ T_{SE}^{3/2} \ e^{\ -h(v_1-v_o)/kT_{SE}} \ \left[\left(\frac{hv_1}{kT_{SE}} + 1 \right)^2 + 1 \right] \qquad (II.39)$$

where $\beta_s = 5.4 \cdot 10^{-6}$ is the dilution factor.

In order to determine the numerical values from the latter expression the value of the electronic temperature which must be adopted is 12,000°K. Indeed, the initial relation (II.13) on which (II.39) ultimately depends results from the observed distribution of the radiation energy in the Balmer series continuum. On the basis of the spectra obtained during the solar eclipse of 1932, Menzel and Cillié (Ref. 48) find a mean value of the electronic temperature T_{SE} equal to 12,000°K.

In adopting this value, we shall note nevertheless that there are variations from one eclipse to another, and that the continuous spectrum of the Balmer series is subject to fluctuations even within the chromosphere.

The numerical results obtained by calculation with the use of expression (II.39) are indicated in graphical form in Figure 11. We see that the radiation emerging from the chromosphere ($\lambda < 910$ Å) does not follow the law of a black body. For lower wave numbers, the total number of quanta reaching the top of the atmosphere is of the order of the number of quanta which can be produced by a black body at a temperature in excess of $5,740^{\circ}$K. However, for a wave number in excess of $1.6 \cdot 10^{5}$ cm^{-1} (or $\lambda \sim 625$ Å), the chromospheric emission surpasses that of a black body at $7,000^{\circ}$K. Hence, the radiation emitted by the sun in the spectral range of $\lambda < 910$ Å does not correspond to the radiation of a black body.

A comparison between the emission of a black body at $12,000^{\circ}$K and the effective chromospheric emission determined by equation (II.39) makes it possible to deduce a law pertaining to the properties of black bodies. In Figure 11, it will be noted that the curve corresponding to a black body at $12,000^{\circ}$K is parallel to the curve which we have deduced by applying (II.39); the difference expressed in log is equal to 5.71. In other words, we find that for a fixed temperature T_{SE}, the minimum number of quanta with $\lambda < 910$ Å which reaches the top of the atmosphere is a constant fraction of the number of quanta which would be emitted by the sun, a black body at a temperature T_{SE}.

B. Emission of Lines of the Lyman Series of Hydrogen

During the reabsorption of the quanta emitted in the Lyman series continuum as a result of processes of recombination of electrons and positive hydrogen ions, part of these quanta undergo a degradation. By virtue of the constitution of the quantum states of hydrogen, emission takes place in the Balmer, Paschen, and Lyman series. However, at the very center of the Lyman series the quanta L_{β}, L_{γ}, ... may be reabsorbed and reemitted in the form of the quanta H_{α}, H_{β} and P_{α}, ... and finally L_{α}. In other words, after a certain number of processes of reabsorptions and emissions, the major part of the energy reabsorbed in the photoionization phenomenon is transformed into L_{α} quanta ($\lambda = 1,215.7$ Å).

From the above, we deduce that the chromospheric emission of the radiations L_β, L , ... of the Lyman series produces lines whose intensity cannot exceed the intensity of the neighboring continuous spectrum. On the contrary, in the case of L_α, its intensity is a function of the entire energy reabsorbed in the process of degradation of the quanta $\lambda < 910$ Å. Hence, in order to obtain an estimate of the energy emitted within the chromosphere by the chromospheric radiation L_α, it is sufficient to consider the reabsorbed energy of the Lyman series continuum.

If we replace the symbols of expression (II.22) by their values T_{SE} 12,000°K, $v_1/c = 109,670$ cm^{-1}, we obtain the number of quanta ($\lambda < 910$ Å) emitted within a radial chromospheric column

$$\int_{v_1}^\infty Q(v)dv = 1.59 \times 10^{19} \text{ quanta sec}^{-1} \text{ cm}^{-2}. \tag{II.41}$$

Since the number of quanta ($\lambda < 910$ Å) emerging from the chromosphere is given by (II.38), we obtain ($T_{SE} = 12,000$°K, $v_1/c = 109,670$ cm^{-1}):

$$\int_{v_1}^\infty Q_1(v)dv = 3.33 \times 10^{14} \text{ quanta sec}^{-1} \text{ cm}^{-2}. \tag{II.42}$$

By comparing these two results, we can conclude that the number of L_α quanta emitted within a radial chromospheric column is equal to $1.59 \cdot 10^{19}$. On the other hand, since the observations of visible chromospheric radiations (H and K of Ca$^+$, for example) indicate the existence of a reabsorption whose theoretical explanation is not sufficient, we have to assume that the emission of L_α, as just determined, represents a maximum.

Consequently, the maximum number of L_α quanta which can reach the top of the atmosphere is equal to

$$1.59 \cdot 10^{19} \cdot 5.4 \cdot 10^{-6} = 8.59 \cdot 10^{13} \text{ quanta sec}^{-1} \text{ cm}^{-2}.$$

This numerical result also shows that the number of L_α quanta exceeds the number of quanta which could be produced by a black body at 6,000°K in the spectral range of $\lambda < 1,350$ Å.

C.   Chromospheric Emission of Helium

Among the radiations emitted in the far ultraviolet ($\lambda\lambda$ 584 Å, 537 Å, ...) by neutral helium, the second line of the fundamental series λ 537 Å lends itself to a determination of the number of quanta emitted by the chromosphere at this wavelength. The higher state 3 $^1P_0$ of the transition 1s ^{1}S - 3p $^1P_0$ (λ = 537 Å) is also the higher state of the transition corresponding to the line λ 5,016 Å which is observed in the chromospheric spectrum. Thanks to the observations made by Menzel and Cillié (Ref. 48), we find that the number of quanta emitted in a transverse column tangent to the solar edge produces $1.62 \cdot 10^5$ erg sec^{-1}cm^{-2}.

If we take relation (II.11) into account, and assume the absence of any reabsorption, with $\theta = 0.78 \cdot 10^{-8}$ cm^{-1}, we find that the radial emission of λ 5,016 Å is given by

$$E_r = E_t (2\pi\theta R)^{1/2} = 2.75 \cdot 10^3 \text{ erg sec}^{-1}\text{cm}^{-2}.$$

Since a quantum at λ 5,016 Å is equivalent to $3.95 \cdot 10^{-12}$ erg, the number of quanta $Q(v_1)$ emitted in a radial column by radiation of λ 5,016 Å is therefore

$$Q(v_1) = \frac{2.75 \cdot 10^3}{3.95 \cdot 10^{-12}} = 7 \cdot 10^{14} \text{ quanta sec}^{-1} \text{ cm}^{-2} \qquad (\text{II.43})$$

The ratio of the probabilities of emission of radiations with λ 537 Å and λ 5,016 Å of He is equal to 40.5. Hence, we deduce the emission of

$Q(v_2)$ within the chromosphere through λ 537 Å

$$Q(v_2) = 2.8 \cdot 10^{16} \text{ quanta sec}^{-1} \text{ cm}^{-2} \qquad \text{(II.44)}$$

In order to determine the number of quanta escaping from the solar atmosphere, we must first take into account the reabsorption produced by chromospheric hydrogen. Let

$$q(v) = q_0(v) \, e^{-\theta_1 z} \qquad \text{(II.45)}$$

be the law of vertical distribution of the quanta emitted within the chromosphere by the radiations of neutral helium. On the other hand, for hydrogen, we have a distribution

$$N(H) = N_0(H) \, e^{-\theta_2 z} \qquad \text{(II.46)}$$

We have already seen that the parameter $\theta \equiv \theta_2$ for hydrogen is

$$\theta_2 = 1.54 \cdot 10^{-8} \text{ cm}^{-1} \qquad \text{(II.47)}$$

whereas for helium, Menzel and Cillié (Ref. 48) find

$$\theta_1 = 0.78 \cdot 10^{-8} \text{ cm}^{-1} \qquad \text{(II.48)}$$

By comparing (II.47) and (II.48), we find that we can write, to an excellent approximation,

$$\theta_2 = 2\theta_1 \qquad \text{(II.49)}$$

If we consider the law (II.25), which applies without restriction to the case under consideration, we have, on the basis of (II.49)

$$q_1(v) = q_0(v) \, e^{-\theta_1 z} \, e^{-x(v) N_0(H)} \int_z^\infty e^{-\theta_2 z} \, dz$$

$$= q_0(\nu)\, c^{-\theta_1 z}\, e^{-\dfrac{\varkappa(\nu)N_0(II)\; c^{--\theta_2 z}}{\theta_2}}$$

$$= q_0(\nu)\, c^{-\theta_1 z}\, e^{-\dfrac{\varkappa(\nu)N_0(II)\; c^{-2\theta_1 z}}{2\theta_1}} \qquad (II.50)$$

In order to obtain the effect of the entire chromosphere, we consider the integral

$$Q_1(\nu) = q_0(\nu) \int_0^\infty e^{-\theta_1 z}\, e^{-\dfrac{\varkappa(\nu)N_0(II)\; c^{-2\theta_1 z}}{2\theta_1}}\, dz \qquad (II.51)$$

By setting $\quad \dfrac{\varkappa(\nu)N_0(II)\; c^{--2\theta_1 z}}{2\theta_1} \equiv \zeta\, e^{-2\theta_1 z} \equiv x^2,$

expression (II.51) can be written

$$Q_1(\nu) = \frac{q_0(\nu)}{\zeta^{1/2}\theta_1} \int_0^{\zeta^{1/2}} e^{-x^2}\, dx \qquad (II.52)$$

where

$$\zeta^{1/2} = \sqrt{\frac{1.25 \times 10^{-18} \times 1.23 \times 10^{14}}{2 \times 0.78 \times 10^{-8}}} = 108.6 \qquad (II.53)$$

Since

$$\int_0^{108.6} e^{-x^2}\, dx \simeq \int_0^\infty e^{-x^2}\, dx = \frac{\sqrt{\pi}}{2} \qquad (II.54)$$

(II.52) can be written, on the basis of (II.44),

$$Q_1(\nu) = q_0(\nu) \sqrt{\frac{\pi}{2\theta_1 N_0(II)\varkappa(\nu)}} = Q(\nu_2) \sqrt{\frac{\pi\theta_1}{2N_0(II)\varkappa(\nu_2)}} \qquad (II.55)$$

Replacing the symbols by their values, we finally obtain

$$Q_1(v_2) = 2.8 \cdot 10^{16} \cdot 8.08 \cdot 10^{-5} = 2.26 \cdot 10^{14} \text{ quanta sec}^{-1} \text{ cm}^{-2}.$$

If the reabsorption at the very center of the line were negligible, the number of quanta (λ 537 $\overset{\circ}{A}$), which should reach the top of the atmosphere, would be given by

$$\beta_s Q_1(v) = 5.4 \cdot 10^{-6} \cdot 2.26 \cdot 10^{14} = 1.22 \cdot 10^{9} \text{ quanta sec}^{-1} \text{ cm}^{-2}$$

$$(\text{II.56})$$

Actually, we should be able to take into account the reabsorption by helium. Since it is not possible to determine this reabsorption theoretically, the exact value of the effective number of quanta emerging from the chromosphere in the lines of the fundamental series of neutral helium cannot be calculated exactly. If we use the radical hypothesis that the quanta reabsorbed in the lines (λ 537 $\overset{\circ}{A}$, λ 522 $\overset{\circ}{A}$, etc.) are finally degraded, the emission will be partly concentrated in the first line of the series λ 584 $\overset{\circ}{A}$. By virtue of (II.56) and taking into account the reabsorption itself, we shall assume that the number of quanta (λ 584 $\overset{\circ}{A}$) reaching the top of the atmosphere is less than 10^9 quanta per second per cm^2.

D. Chromospheric Eruptions

Among the solar eruptions revealed by any method of observation, only the chromospheric eruptions are characterized by noticeable radiative properties. Thus, the eruptive emission proper, which is always monochromatic, may, in H_α light, equal or even exceed the intensity of the neighboring continuous spectrum. In Table 2, we have collected the principal characteristics of the eruption (Ref. 50) which are necessary for a determination of the energy usable for the ionization of the atmosphere. The surface area is represented as a function of the surface of the solar disk, whereas the brightness corresponds to an arbitrary scale of 1 to 5. The intensity of an eruption is expressed as a function of the intensity of $H_\alpha = 1.35 \cdot 10^7$ erg per second per cm^2.

Table 2. Solar Eruptions

	$1 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$7.5 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	1.25 to $4 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$2.5 \cdot 10^{-3}$
Surface area								
Observed brightness		1.3	1.7		2.3 to 2.6		3.9	
Mean brightness	1			2		3	4	5
Intensity as a function of H_α	1.8			2.8		3.8	7.9	(10)

From this value of the intensity of H_α and from the data given by Table 2, it is easy to determine the number of L_α quanta (λ=1,215.7 Å) emitted by an eruption, where the reabsorption and reemission are not considered, and whose brightness and surface are fixed. Keeping in mind the distance from the earth to the sun, we finally deduce the number of quanta usable at the top of the atmosphere.

Since an H_α quantum is equal to $3 \cdot 10^{-12}$ erg, the number of H_α quanta emitted by a surface of 1 cm^2 is equal to $4.5 \cdot 10^{18}$. The ratio of the quanta emitted by L_α and H_α is of the order of 4, if we consider the capture of hydrogen at the different levels and the resulting spontaneous emission. Thus, the number of L_α quanta emitted per second per cm^2 of solar surface is equal to $4.5 \cdot 10^{18} \cdot 4 = 1.8 \cdot 10^{19}$ quanta.

For an eruption, the eruptive number of quanta Q_{L_α} reaching the top of the atmosphere will be given by the formula

$$Q_{L_\alpha} \text{ eruptive} = 3.6 \cdot 10^{19} \cdot I \cdot \frac{Sr^2}{R^2} \qquad (II.57)$$

where I is the intensity of the eruption as a function of the intensity of H_α, S is the fraction of the surface of the solar disk occupied by the eruptions, and $r^2/R^2 = 2.16 \cdot 10^{-5}$ is the reduction factor which takes into account the distance from the earth to the sun.

By introducing the numerical values of Table 2 into the formula (II.57), we obtain the following results:

Mean brightness of eruption	L_α quanta per second per cm^2 at the top of the atmosphere
1	$7 \cdot 10^9$
2	$1 \cdot 10^{11}$
3	$7.4 \cdot 10^{11}$
4	$2.3 \cdot 10^{12}$
5	$9.7 \cdot 10^{12}$

A comparison of these values, which gives the number of L_α quanta

reaching the top of the atmosphere during eruptions, with the number of quanta emitted by a black body at various temperatures, reveals the importance of the radiation of eruptions. Thus an eruption with a mean brightness equal to 3 emits a number of L_α quanta exceeding the number of

quanta ($\lambda < 1{,}350$ Å) produced by a black body at $5{,}740^\circ$K. Similarly, an eruption with a mean brightness equal to 4 emits a number of L_α quanta

which is greater than the number of quanta ($\lambda < 1{,}350$ Å) produced by a black body at $6{,}000^\circ$K. As far as the comparison between the number of quanta emitted by chromospheric L_α and eruptive L_α is concerned, no con-

clusion is possible because the effect of the reabsorption of chromospheric L_α is not known. Finally, let us note that the position of the

eruption within the chromosphere could affect the number of usable quanta, since the effect of reabsorption and of electron recombination is different depending upon the optical thickness.

Section 4. Variations of the Ultraviolet Solar Emission

That the values which we have deduced for the ultraviolet emission of the sun are average values is amply indicated by the data used in the calculations. However, although the observations do not reveal any variation in the emission of visible radiation, they do show that the photosphere is not uniform. Indeed, certain regions appear as zones of particular excitation where the emission lines increase in intensity during observations in total light or during spectroheliographic observations of the facular plages. The fact that the faculae are quite visible near the edge of the disk where the observer is located, opposite the atmospheric layer with its largest thickness, indicates that these faculae are more elevated than the general level of the photosphere. They correspond to facular plages, which manifest the variations of the chromospheric emission in spectroheliographic pictures. Besides, one can readily see

that the radiation $\lambda < 910$ Å originates from the upper levels of the chromosphere. Let us refer to formulas (II.22 and 38), which give respectively the number of quanta emitted within the chromosphere and the number of quanta emerging from the chromosphere. By writing

$$\int_\nu^\infty Q_1(\nu)\,d\nu = e^{-\theta z} \int_\nu^\infty Q(\nu)\,d\nu \qquad (\text{II}.58)$$

where $\theta = 1.54 \cdot 10^{-8}$ cm^{-1} and where z denotes the effective height of the chromospheric emission, we deduce the following value of z (II.41 and 42):

$$z = \frac{1}{\theta} \, log_e \frac{\int_{\nu_0}^{\infty} Q_1(\nu)\,d\nu}{\int_{\nu_0}^{\infty} Q(\nu)\,d\nu} = \frac{1}{\theta} \, log_e \frac{1.59 \times 10^{19}}{3.33 \times 10^{14}} = 7 \times 10^8 \text{ cm} \approx 7000 \text{ km} \qquad (II.59)$$

Hence, the effective height of the chromospheric emission corresponds to chromospheric levels characterized by the greatest abundance of facular plages; hence, the general chromospheric emission will be subject to variations of the number of facular plages. Observation has shown that the latter do represent the 11-year solar activity. Consequently, the 11-year solar activity must of necessity be expressed in the possible ionization of the atmosphere by a variation related to the abundance and intensity of the facular plages.

In order to determine quantitatively the difference in the energy supplied for the terrestrial ionization between the minimum and the maximum of solar activity, one would have to have the absolute values of the total chromospheric emission in the course of an 11-year period. However, no determination of this type has as yet been performed, and we must, therefore, content ourselves with correlations between the values of the brightness of facular plages based on an arbitrary scale and the values of the electron concentration in various regions of the ionosphere.

In the present state of solar observations, a determination of the effect of the 11-year activity can be attempted only by investigating the ultraviolet emission of the faculae. To this end, we shall take the generally adopted temperature of 7,500°K as the temperature of the facular area. In addition, let us consider the data obtained from the observation[1] of the variation of the surface area of the faculae in the course of a solar activity cycle. From the general expression (II.3) we can calculate the number of quanta emitted under the conditions which we have just indicated. The results are presented in graphical form in Figure 14. We see readily that the total surface of the faculae is of

the order of 10^{-3} times the surface of the solar surface; the flux of

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[1] During the solar activity maxima of 1889, 1894 and 1907, the surface occupied by the faculae was of the order of $2.5 \cdot 10^{-3}$, $3.5 \cdot 10^{-3}$ and $3 \cdot 10^{-3}$ times the solar surface. For these results, due to Maunder, see Nicolet, Ref. 47, Figure 2.
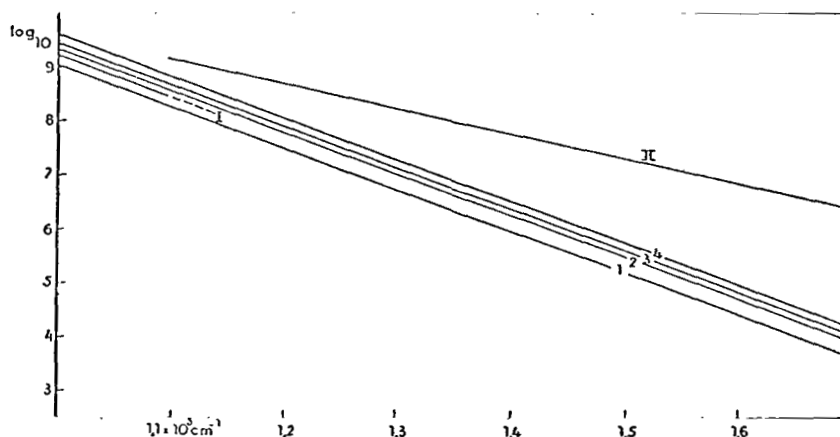
Figure 14

I, Black body, $T_S = 5,740°K;$

II, chromospheric radiation, $T_{SE} = 12,000°K.$

Radiation of the faculae, $T_F = 7,500°K;$

1, surface, $S_F = 1 \cdot 10^{-3} S_\odot;$ 2, $S_F = 2 \cdot 10^{-3} S_\odot;$

3, $S_F = 2.5 \cdot 10^{-3} S_\odot;$ 4, $S_F = 3.5 \cdot 10^{-3} S_\odot$

facular radiation is always less than that of the normal solar radiation

$(\lambda < 1,000 \text{ Å})$. The increase in the total surface area of the faculae corresponding to the increase in solar activity produces a radiation flux greater than that of normal radiation in certain specific spectral regions. In order to appraise its effective role in the ionization of the earth's atmosphere, we must know the atoms and molecules susceptible of being ionized. This will be the subject of the following chapters.

Section 5. Conclusions

Important conclusions result from the study which we have just made on the special features of the radiation emitted by the sun in the unobservable ultraviolet region. First, two spectral regions should be distinguished for which the radiative properties are totally different,

mainly the regions with wavelengths above or below 910 Å. In the

spectral region of $\lambda > 910$ Å, the spectral distribution corresponds to that of a black body at the temperature of 5,740°K. However, because of the behavior of solar hydrogen, photospheric radiation with wavelengths

of less than 910 Å is negligible in the presence of chromospheric radiation.

Chromospheric radiation ($\lambda < 910$ Å, capable of ionizing atomic oxygen, molecular and atomic nitrogen, and helium) corresponds to the known reabsorbed radiation of the continuum of the Lyman series for hydrogen. The spectral distribution may be likened to the spectral distribution of a gray body. Actually, the minimum flux of chromospheric radiation

($\lambda < 910$ Å) is equal to the radiation flux of a black body at 12,000°K (average value of the electronic temperature subjected to variations)

multiplied by a constant factor, $\Phi = 1.96 \cdot 10^{-6}$. A numerical application (see Figure 11) indicates the peculiar behavior of this chromospheric radiation with respect to black bodies whose temperatures lie between 5,740°K and 7,500°K.

The emission of monochromatic radiations may be superimposed a

priori onto the continuous photospheric emission ($\lambda > 910$ Å) and chromo-

spheric emission ($\lambda < 910$ Å). From our study it follows that the radia-

tion (λ 584 Å) of helium may have an appreciable intensity. However,

among the monochromatic chromospheric radiations, the L_α line ($\lambda =$

1,215.7 Å) is distinguished by an intensity which is higher than that of the neighboring continuous spectrum.

In addition, the effective source of the 11-year variation of solar activity has been found in the variation of the faculae and facular plages, which participate in the chromospheric emission.

Finally, the monochromatic radiation L_α ($\lambda = 1,215.7$ Å) emitted by

chromospheric eruptions and calculated as a function of the brightness and surface area of the eruptions may be greater than the radiation

($\lambda < 1,350$ Å) of a black body at 5,740°K.

CHAPTER III.   CONSTITUTION AND COMPOSITION OF THE ATMOSPHERE

Section 1.   Introduction

A study of the constitution of the atmosphere requires the knowledge of physical and chemical data. Soundings by means of standard meteorological techniques make it possible to determine the properties of the atmosphere up to an altitude of 30-35 km. As far as higher regions are concerned, one must have recourse to the observation of phenomena such as the absorption of atmospheric ozone, the propagation of sound waves, luminous nocturnal clouds, twilight phenomena, the light of auroras and of the night sky, and the propagation of radio waves. These various phenomena are the only means of investigation which enable us to determine the pressure, temperature, and chemical constituents as a function of altitude.

By definition, the atmospheric pressure at any point is the weight of a vertical column of air of unit cross section whose base has its center at a given point and which extends up to the top of the atmosphere. Let P, ϱ, and T be, respectively, the pressure, density and absolute temperature at altitude z, and let $P + dP$ be the pressure at altitude $z + dz$. By definition, dP is the weight of a slice of air of unit cross section and thickness dz. Hence, g being the acceleration due to gravity which will be considered constant, the equation of atmospheric statics will be

$$dP = -g\varrho\,dz \qquad\qquad (III.1)$$

If the different atmospheric constituents at altitude z have molecular masses m_j (mass of a molecule) and if the number of molecules per cm^3 is N_j (j indicates this species), we have

$$\varrho = N_1 m_1 + N_2 m_2 + \ldots\ldots \equiv NM \qquad\qquad (III.2)$$

with
$$N = N_1 + N_2 + \ldots. \qquad\qquad (III.3)$$

Relations (III.2 and 3) make it possible to write equation (III.1) in the form

$$\frac{dP}{dz} = -g N M \tag{III.4}$$

If is assumed that the law of ideal gases

$$P\mathcal{V} = \mathcal{R}T \tag{III.5}$$

may be applied to each of the atmospheric gases, where T is the absolute temperature, $\mathcal{R}$ is the gas constant per mole or universal molar constant of ideal gases, $\mathcal{V}$ is the molar volume, i.e., the volume occupied by one mole or $\mathcal{N}$ molecules.

Since N is the total number of molecules per cm^3, we have the ratio

$$\mathcal{V} = \frac{\mathcal{N}}{N} \tag{III.6}$$

and hence, taking (III.6) into account, the gas law (III.5) may be written as

$$P = N\frac{\mathcal{R}}{\mathcal{N}}T = NkT \tag{III.7}$$

where $k = \frac{\mathcal{R}}{\mathcal{N}}$ is Boltzmann's constant, the gas constant relative to one

molecule.

Section 2. Vertical Distribution of the Constituents of the Atmosphere

By taking into account the ideal gas equation (III.7) in equation (III.4), i.e., by replacing dP in (III.4) by its value obtained from (III.7), we get the general equation

$$\boxed{\frac{dN}{N} + \frac{dT}{T} = -\frac{gM}{kT}\,dz} \tag{III.8}$$

By setting

$$\frac{kT}{Mg} \equiv H \qquad\qquad (III.9)$$

which defines the height of the homogeneous atmosphere, we can write (III.8)

$$\frac{dN}{N} + \frac{dT}{T} = -\frac{dz}{H} \qquad\qquad (III.10)$$

Since the atmosphere is essentially made up of gases of different species, the latter may be mixed or be in a diffusion equilibrium. In the former case, equation (III.10) applies directly. In the second case, a concentration of each constituent of the gas is subject to the law of statics (III.4) and to the law of ideal gases (III.7). We then write equation (III.10) in the form

$$\frac{dN_j}{N_j} + \frac{dT}{T} = -\frac{dz}{H_j} \qquad\qquad (III.11)$$

where $H_j \equiv \dfrac{kT}{gm_j}$ $\qquad$ (j = 1, 2, 3, ...)

Equations (III.11) implicitly express Dalton's law, according to which the total pressure is equal to the sum of the partial pressures exerted separately by the various constituents.

Equations (III.10 or 11) are fundamental equations which make it possible to determine the vertical distribution of the particle concentration, if the laws of variation of M and T with altitude are known. Conversely, if the molecular concentration is known at a given altitude, the ratio of the other two parameters, temperature and molecular mass, can be determined. We shall consider some simple cases which may represent cases of practical importance in certain regions of the atmosphere. We shall make use of equation (III.10), since the conclusions pertaining to an average constituent may apply to a constituent of species j.

Case 1. Let us consider the simple case,

T = constant, M = constant, and hence H = constant. Equation (III.10) is then written

$$\frac{dN}{N} = -\frac{dz}{H} \qquad\qquad (III.12)$$

and by integration,

$$N = N_0 \ e^{-z/H} \tag{III.13}$$

where N is the molecular concentration at altitude z and N_0 is the molecular concentration at altitude $z = 0$, considered as the starting level.

If we wish to know the total number $\mathfrak{N}$ of particles in a vertical column of unit cross section of fixed thickness z_1, it will suffice to integrate relation (III.13)

$$\mathfrak{N} = N_0 \int_0^{z_1} e^{-z/H} dz = N_0 H \ (1 - e^{-z_1/H}) \tag{III.14}$$

where N_0, which is a concentration at level $z = 0$, is therefore the number of atoms per cm^3 at the base of the column.

In the practical case where $e^{-z_1/H} = 0.01$ may be neglected as compared to 1, i.e., when $z_1/H \geqslant 4.5$, we can write to the indicated approximation that the total number of atoms in a column of thickness $z_1 \geqslant 4.5$ H is given by

$$\boxed{\mathfrak{N} = N_0 H} \tag{III.15}$$

Case 2. Let M = constant and let us consider a linear increase of the temperature with altitude

$$T = T_0(1 + \xi z), \qquad \xi > 0 \tag{III.16}$$

Hence, taking (III.9) into consideration, we have

$$H = H_0(1 + \xi z). \tag{III.17}$$

When (III.16 and 17) are taken into account, equation (III.10) becomes

$$\frac{dN}{N} = - \frac{\xi H_0 + 1}{H_0(1 + \xi z)} dz \qquad (III.18)$$

Hence, by integrating,

$$N = N_0(1 + \xi z)^{- \frac{1}{\xi H_0} - 1} \qquad (III.19)$$

The total number $\mathscr{N}$ of particles in a column of fixed thickness z_1 is obtained by integrating (III.19)

$$\mathscr{N} = N_0 \int_0^{z_1} (1 + \xi z)^{- \frac{1}{\xi H_0} - 1} dz = N_0 H_0 \left[1 - (1 + \xi z_1)^{- \frac{1}{\xi H_0}} \right] \qquad (III.20)$$

By neglecting in comparison with unity

$$(1 + \xi z)^{- \frac{1}{\xi H_0}} \leqslant 0.01 \qquad (III.21)$$

i.e., keeping only the first term of the expansion in series, since $(\xi z)^2 < 1$, we have

$$\boxed{\mathscr{N} = N_0 H_0} \qquad (III.22)$$

when

$$\frac{z_1}{H_0} \geqslant 4.5$$

Case 3. For M = constant, let us consider a linear decrease of the temperature

$$T = T_0(1 - \xi z) \quad , \quad \xi > 0 \qquad (III.23)$$

and, by virtue of (III.9),

$$H = H_0(1 - \xi z) \qquad (III.24)$$

On the basis of (III.23 and 24), equation (III.10) becomes

$$\frac{dN}{N} = \frac{H_o \xi - 1}{H_o} \frac{dz}{1 - \xi z} \qquad \text{(III.25)}$$

By integration, we obtain the vertical distribution of the particle concentration

$$N = N_o (1 - \xi z)^{\frac{1}{\xi H_o} - 1} \qquad \text{(III.26)}$$

The total number of particles in a column of thickness z_1 is given by the integral of (III.26)

$$\mathfrak{N} = N_o \int_o^{z_1} (1 - \xi z)^{\frac{1}{\xi H_o} - 1} dz$$

and, the exponent being positive,

$$\mathfrak{N} = N_o H_o \left[1 - (1 - \xi z_1)^{\frac{1}{\xi H_o}} \right] \qquad \text{(III.27)}$$

Since the concentration N must be positive and not zero, we always have $\xi z < 1$. Hence, in the practical case where

$$(1 - \xi z)^{\frac{1}{\xi H_o}} \leqslant 0.01 \qquad \text{(III.28)}$$

i.e., by keeping only the first term of the expansion in series, we have, with the indicated approximation, (III.27)

when $\frac{z_1}{H_o} \geqslant 4.5$

$$\boxed{\mathfrak{N} = N H_o} \qquad \text{(III.29)}$$

Case 4. Let T = constant and

$$M = M_o(1 - \xi z) \tag{III.30}$$

and consequently,

$$H = \frac{H_o}{1 - \xi z} \tag{III.31}$$

Taking into account (III.31), we can write equation (III.10) as

$$\frac{dN}{N} = - \frac{(1 - \xi z)dz}{H_o} \tag{III.32}$$

Hence, by integration, we get the vertical distribution of the particle concentration

$$N = N_o \, e^{- z/H_o(1 - \frac{\xi z}{2})} \tag{III.33}$$

If $\frac{\xi z}{2} < 1$, i.e., the concentration N at altitude z is always less than N_0 at the level z = 0, we write relation (III.33) in the approximate form

$$N \simeq N_o \, e^{- z/H_o} \tag{III.34}$$

This approximate representation of the variation of the concentration N with the altitude is of the same type as that corresponding to an isothermal atmosphere.

Relations (III.13, 19, 26 and 33) may be considered fundamental relations which make it possible to determine the constitution of the atmosphere when sufficient data are available on the temperature and composition. In the lower atmosphere (z < 35 km), aerological soundings provide both the vertical distribution of the pressure and of the temperature, and thus, the uniformity of the composition being considered, the vertical distribution of the constituents. The upper layers (z > 35 km) cannot be studied without the use of hypotheses concerning the behavior of one or the other physical element. Many authors base their determination of the structure of the upper atmosphere on data obtained

from tropospheric observations. However, the results obtained cannot be wholly accepted in any of these cases.

Below 90 km, despite certain discrepancies, recent determinations (Ref. 51) of the structure of the middle atmosphere (35-90 km) are in essential agreement. This means that the use of relations (III.13, 19, 26) is justified in the middle atmosphere where, if the average molecular mass remains constant, we consider a probable distribution of the temperature, deduced from indirect observational data such as those on the absorption of ozne, the propagation of sound waves, the luminescence of meteors and luminous night clouds. Thus, we can admit the atmospheric distribution determined by Penndorf (Ref. 52) as a result of a critical study of the various phenomena observable in the middle atmosphere.

As far as the upper atmosphere ($z \geqslant 90$ km) is concerned, we shall show, in this chapter, by a discussion of the molecular mechanisms that the constitution is completely different from that of lower layers. Hence, it is necessary to consider a priori, for the vertical distribution of the constituents, the laws which will be applicable to the upper atmosphere.

To this end, let us again consider the laws (III.13, 19, 26) which yield, to the indicated approximation, the relations (III.15, 22, 23), the latter being identical. In other words, if the variations of the parameters of equation (III.10) are fairly simple, the total number $\mathfrak{N}$ of particles in a column of thickness z_1 is always given by

$$\mathfrak{N} = N_0 H_0 \qquad \text{(III.35)}$$

when the following condition is applicable:

$$\frac{z_1}{H_0} \geqslant 4.5 \qquad \text{(III.36)}$$

For the upper atmosphere, we assume to a first approximation that the vertical distribution follows a simple law in a layer of fixed thickness. For such a layer, we assume that the total number $\mathfrak{N}$ of molecules is given by the expression

$$\mathfrak{N} = N_0 h \qquad \text{(III.37)}$$

which may result from an exponential distribution.

$$N = N_0 \, e^{-z/h} \tag{III.38}$$

in an atmosphere which is not necessarily isothermal. In (III.38), the parameter h is the rate of logarithmic decrease of the molecular concentration with the altitude.

By considering this equation (III.38), we assume implicitly that the general equilibrium equation along the vertical is not necessarily an equation of statics, but an equation which can take into account the most diverse effects. In certain special cases, it will be possible to assume that the general equilibrium equation corresponds to the equation of statics; we shall then have, for the isothermal case,

$$h \equiv H \tag{III.39}$$

this means that the rate of logarithmic decrease of the molecular concentration h is identical to the height H of the homogeneous atmosphere.

Section 3. The Upper Atmosphere

The problem of the structure of the upper atmosphere ($z \geqslant 90$ km) differs completely from that of the middle atmosphere, since all the constituents are no longer in the molecular form. In particular, it is well known (Ref. 53) that the oxygen molecule undergoes a photodissociation in the atmospheric region above 80 km. However, the position and dissociation maximum of molecular oxygen and a fortiori the vertical distribution of atomic and molecular oxygen cannot be fixed, except on the basis of uncertain hypotheses. Depending on the hypothesis, the dissociation maximum is located at very different altitudes. Since the E region is located in the atmospheric range of 100 to 130 km, the structure of the atmosphere should be precisely determined. Furthermore, the physical state resulting from the dissociation should give rise to a series of questions concerning the behavior of the other constituents. We are going to show, successively, that oxygen is dissociated into atoms, that nitrogen is partly dissociated, that the NO molecule exists in a fixed region, that helium is present in appreciable amounts, and we shall finally arrive at a structure of the upper atmosphere that is radically different from the structure assumed up to the present time.

A. Dissociation of the Oxygen Molecule

In order to determine the properties of the zone of decomposition of molecular oxygen into atoms, we must know the mechanisms of dissociation and recombination. To this end, we assume the medium to be made up of oxygen molecules (O_2), oxygen atoms (O), and other particles or third bodies (M), whose respective quantities per cm^3 are $N(O)_2$, $N(O)$ and $N(M)$.

If D is the photodissociation coefficient, we shall denote by

$$N(O_2) \cdot D$$

the number of photodissociations of O_2 molecules per cm^3 per second; if R represents the recombination coefficient,

$$N^2(O) \cdot R$$

denotes the number of molecular recombinations per cm^3 per second. Hence, if t is the time, the state of dissociation will be defined at any instant by

$$\frac{\delta N(O_2)}{\delta t} = N(O_2) \cdot D - R \cdot N^2(O) \qquad (III.40)$$

In the case of a stationary state during the day, we shall have the statistical equilibrium equation

$$\frac{N^2(O)}{N(O_2)} = \frac{D}{R} \qquad (III.41)$$

In order to explain this relation it is necessary to find the respective values of the coefficients D and R which depend on the most important elementary mechanisms occurring in the upper atmosphere.

1. Case of dissociation

Oxygen is located in the radiation field of the sun, whose diluted radiation is given by relation (II.1). The O_2 molecules may be dissociated; the part $h v_0$ of the absorbed energy hv corresponding to the photodissociation potential is used to decompose the molecule, and the excess energy $h(v - v_0)$ will be transformed into the translational energy of the

atoms. In order to calculate the number of absorption processes producing the dissociation, we must know the absorption coefficient relative to the transition to the dissociated state. The absorption coefficient being known (Ref. 54),[1] the number of photodissociations per cm^3 per second is expressed by

$$N(O_2) \cdot D = N(O_2) \, \varkappa Q(z) \qquad (III.42)$$

where $\varkappa$ is an average value of the absorption coefficient (Ref. 54) and $Q(z)$ is the number of solar quanta reaching the atmospheric region of altitude z where the photodissociation is being studied.

In order to take into account the fact that prior to reaching a certain altitude z, the dissociated radiation may undergo absorption in the course of its passage through the upper layers, we shall assume that the number of quanta reaching the altitude z is given by the relation

$$Q(z) = Q_\infty \, e^{-\tau}$$

where Q_∞ is the number of quanta reaching the top of the atmosphere and

where τ is the optical thickness defined by ($h_\odot$ = angle of altitude of the sun)

$$d\tau = \frac{\varkappa N(O_2) \, dz}{\sinh_\odot}$$

---

[1]Ladenburg and Voorhis (Ref. 54) have determined experimentally the value of the oscillation force (f = 0.193) of the continuum of photodissociation of oxygen at λ 1,750 Å. With relation $\int \varkappa(\nu) d\nu = \frac{\pi e^2}{mc} f$, a mean value, $\varkappa$, of the absorption coefficient is given by

$$\varkappa = \int_{\nu_1}^{\nu_2} \frac{\varkappa(\nu) d\nu}{\nu_2 - \nu_1} = 8.2 \cdot 10^{-18} \, cm^2,$$

with $\nu_2 = 77,000$ cm^{-1} and $\nu_1 = 57,100$ cm^{-1}. For a variation of $\varkappa$ as a function of ν, see Figure 15.

Taking the latter two relations into account, we can immediately write (III.42) as

$$N(O_2) \times D = N(O_2) \varkappa Q_\infty \, e^{-\frac{\varkappa}{\sin h_\odot} \int_z^\infty N(O_2)dz} = N(O_2)D_\infty e^{-\tau} \qquad \text{(III.43)}$$

By introducing into (III.43) the value of Q_∞ given by (II.3), we have

$$D = \frac{8\pi k^3}{c^2 h^3} \beta_s T_s^3 \varkappa \left\{ e^{-h\nu/kT_s} \left[\left(\frac{h\nu}{kT_s} + 1 \right)^2 + 1 \right] \right\}_{\nu_2}^{\nu_1} e^{-\frac{\varkappa}{\sin h_\odot} \int_z^\infty N(O_2)dz} \qquad \text{(III.44)}$$

i.e., the final expression of the coefficient D.

Replacing the symbols by their numerical values ($T_S = 5,740°K$), we have

$$D = D e^{-\tau} = 3.03 \times 10^{-4} e^{-\frac{8.2 \times 10^{-18}}{\sin h_\odot} \int_z^\infty N(O_2)dz} \qquad \text{(III.45)}$$

2. Case of recombination

A priori, three recombination processes may be involved in the case of oxygen. They are as follows:

(1) Recombination via triple collisions according to the equation

$$O(^3P) + O(^3P) + M \rightarrow O_2 + M \qquad \text{(III.46)}$$
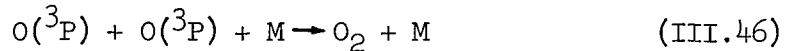
where the third particle captures the recombination energy in the form of excitation or kinetic energy.

(2) Radiative recombination of two normal atoms

$$O(^3P) + O(^3P) \rightarrow O_2 + h\nu; \qquad \text{(III.47)}$$
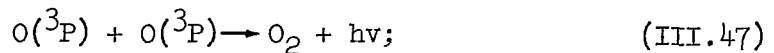
this process is the reverse of the absorption of the telluric bands of oxygen or Herzberg bands leading to dissociation into two normal atoms.

(3) Radiative recombination of a normal atom and an excited atom

$$O(^3P) + O(^1D) \longrightarrow O_2 + h\nu; \qquad\qquad (III.48)$$
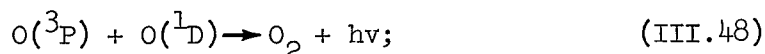
this process is the reverse of the absorption of Schumann-Runge bands. The relative values of the three processes (III.46, 47 and 48) depend on the recombination probabilities in double or triple collisions. From the results of the kinetic theory and spectral properties, it is possible to determine which of the various processes are the most important.

Let us assume first that the number of double collisions $\mathfrak{N}(A,B)$

per second per cm^3 between particles A and B whose concentrations are $N(A)$ and $N(B)$ is given by the Jeans formula (Ref. 55)

$$\mathfrak{N}(A,B) = N(A)N(B)\sqrt{8\pi}\sigma_{AB}^2 \left(\frac{m_A + m_B}{m_A m_B}\right)^{1/2} (kT)^{1/2} \qquad (III.49)$$

where m_A and m_B are the masses of the particles A and B, σ_{AB} is the distance between the centers of the two particles at the instant of collision, k is Boltzmann's constant, and T is the temperature.

For the determination of triple collisions, let us consider three species of particles $N(A)$, $N(B)$, and $N(M)$, characterized by their masses m_A, m_B, and m_M and their distances from the centers during collisions, σ_{AB} and σ_{AM}. We define[1] the number of triple collisions $\mathfrak{N}(A,B,M)$ per cm^3 per second by the relation

$$\mathfrak{N}(A,B,C) = \mathfrak{N}(A,B) \times \omega_{AB} \qquad\qquad (III.50)$$

where ω_{AB} is the probability of a triple collision of the third particle with one of the other two particles undergoing a double collision. In

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[1] See E. Rabinowitch, Trans. Faraday Soc., 33, 283, 1937, and references therein.

other words, we assume that during the collision of the first two par-
ticles A and B, there is a probability, ω_{AB}, that a third particle, M,
will collide with one or the other of the two particles considered.

If we introduce the duration of the double collision, τ_{AB}, the
probability, ω_{AB}, is expressed by the relation

$$\omega_{AB} = \frac{\mathfrak{N}(A,M)}{N(A)} \tau_{AB} \simeq \frac{\mathfrak{N}(B,M)}{N(B)} \tau_{AB} \tag{III.51}$$

By virtue of (III.49 and 51), relation (III.50) applied to oxygen
$O = A = B$ may be written as

$$\mathfrak{N}(O, O, M) = N^2(O)\ N(M) 8\pi\sqrt{2}\sigma_{O_2}^2\ \sigma_{OM}^2\ \tau_{O_2} \left(\frac{m_O + m_M}{m_O^2\ m_M}\right)^{1/2} kT \tag{III.52}$$

Assuming that the kinetic collision cross section corresponds to
the effective recombination cross section, the preceding relation
(III.52) provides the recombination number of the oxygen molecule per
triple collision.

The determination of the frequencies of radiative recombination
processes requires the knowledge of the recombination probability in the
course of a double collision, determined by formula (III.49) of the
kinetic theory. This probability may be calculated by assuming that in
the course of the collision of the two atoms, the pseudo-molecular as-
sociation may lose the excess energy resulting from the possible recom-
bination in the form of radiation. If τ is the duration of the colli-
sion and ω_r is the probability of radiative recombination, we can write

$$\omega_r = \tau\ A_{ji}$$

where A_{ji}[1] is the probability of emission. Consequently, we obtain the
number of radiated recombinations of O_2 by means of relation (III.49)

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[1]The values of A_{ji} are calculated in the following manner: (1) for the
Schumann-Runge system by the relation $A_{ji} = \frac{8\pi^2\varepsilon^2\nu^2}{mc^3}f_{ij} = 6.2 \cdot 10^8$;

$$N^2(O) \times R = N^2(O) \sqrt{16\pi\sigma_{O_2}^2} \, \omega, \left(\frac{kT}{m_O}\right)^{1/2} \qquad \text{(III.53)}$$

By replacing the symbols in relations (III.52 and 53) by their numerical values, we successively obtain the following results for the recombination coefficients:

(1) Recombination via triple collision of normal atoms (III.52)

$$R(O_2, M) = 4.44 \cdot 10^{-32} \, N(M) \qquad \text{(III.54)}$$

(2) Radiative recombination via collision of normal atom $O(^3P)$ and excited atom $O(^1D)$ in the Schumann-Runge system

$$R(O_2, {}^1D)_S = 2 \cdot 10^{-14} \qquad \text{(III.55)}$$

If the ratio of excited atoms $O(^1D)$ to normal atoms $O(^3P)$ is denoted by ζ, we write that the number of recombinations per second per cm^3 is equal to

$$N^2(O) \, R(O_2, {}^3P)_S = N^2(O) \, \zeta \cdot 2 \cdot 10^{-14} \qquad \text{(III.55')}$$

(3) Radiative recombination via the collisions of two normal atoms in the system of telluric bands

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(Footnote continued from preceding page)
(2) for the atmospheric bands by the experimental result of Mecke (Trans Faraday Soc., 27, 359, 1931), who determined the lifetime of the higher state to be 7 sec, whence $A_{ji} = 1/7 = 0.143 \, sec^{-1}$; (3) for Herzberg bands, by assuming on the basis of experimental results that the absorption coefficient of this system is 10^7 times smaller than that of the Schumann-Runge system; $A_{ji} = 2.4 \cdot 10^3$. If the temperature is of the order of $300^\circ K$, $\tau = 8 \cdot 10^{-13}$ sec. For molecular spectra, see for example the reference in V. Henri, "Tables annuelles des constantes et données numériques (Annual Tables of Numerical Constants and Data), fasc. 11, March 1937.

$$R(O_2, {}^3P)_T = 4.6 \cdot 10^{-24} \qquad (III.56)$$

(4) Radiative recombination via collisions of two normal atoms in the system of Herzberg bands

$$R(O_2, {}^3P)_H = 7.6 \cdot 10^{-20} \qquad \text{. (III.57)}$$

3. Equilibrium equation

Given that the coefficients of dissociation and recombination are known (III.44 and 45) and (III.52 and 53; 54, 55', 56 and 57), respectively, we write the equation of statistical equilibrium (III.41) in the final form

$$\frac{N^2(O)}{N(O_2)} = \frac{D_\infty \, e^{-\dfrac{\varkappa}{\sin h_\odot} \int_z^\infty N(O_2)\, dz}}{R(O_2, M) + \zeta R(O_2, {}^3P)_S + R(O_2, {}^3P)_T + R(O_2, {}^3P)_H}$$

$$= \frac{3.03 \times 10^{-4} \times e^{-\dfrac{8.2 \times 10^{-18}}{\sin h_\odot} \int_z^\infty N(O_2)\, dz}}{4.44 \times 10^{-32} N(M) + \zeta \times 2 \times 10^{-14} + 4.6 \times 10^{-24} + 7.6 \times 10^{-20}} \qquad (III.58)$$

By setting

$$R_1 N(M) \equiv R(O_2, M)$$

to represent the action of triple collisions on the recombination and

$$R_2 \equiv \zeta \cdot 2 \cdot 10^{-14} + 4.6 \cdot 10^{-24} + 7.6 \cdot 10^{-20}$$

to represent the action of double collisions on the recombination, we finally write (III.58) in the form

$$\boxed{\frac{N^2(O)}{N(O_2)} = \frac{D_\infty \, e^{-\dfrac{\varkappa}{\sin h_\odot} \int_z^\infty N(O_2)\, dz}}{R_1 N(M) + R_2}} \qquad (III.59)$$

4. Spectral properties

In order to avoid introducing any arbitrary hypothesis on the vertical distribution of the constituents in the region of dissociation of O_2, it is necessary to refer to the conclusions which can be drawn from spectral observations.

Forbidden transitions of atomic oxygen are observed in the spectrum of the night sky and of the aurora. We have discussed (Ref. 56) the conditions of emission at the green line $(\lambda\ 5{,}577\ \overset{o}{A})$ and red lines $(\lambda\lambda\ 6{,}300\text{-}6{,}363\ \overset{o}{A})$ of the neutral atom OI.

Since the triple collision process can apply only to the lowest region of the upper atmosphere, we have introduced (Ref. 57) the possible effect of the absence of the dipole of the N_2 and O_2 molecules. This effect (Ref. 58) would make it easier to interpret the increase observed in the ratio of the intensities of the red lines to the intensity of the green line in the auroral spectrum. In fact, a complete theory of the night sky emission should take into account the ionospheric results which we obtain in Chapter V.

In addition to this nocturnal or auroral emission, attention should be focused primarily on the twilight reinforcement of the intensity of the red transition, in which the green line does not undergo any variations. We can adopt the simple hypothesis of a resonance effect and an emission which is unperturbed by deactivating collisions. In this case, the emission should be proportional to the number of atoms. Or it may be suggested (Ref. 56) that the photochemical decomposition is not negligible in the twilight formation of the $O(^1D)$ atoms, the higher state of the red radiations transition. In this case, this phenomenon could be involved in the twilight reinforcement in accordance with the process

$$O_2 + h\nu\ (\lambda < 1750\ \text{Å}) \rightarrow O(^3P) + O(^1D)$$
$$O(^1D) \rightarrow O(^3P) + \lambda\lambda\ 6300\text{-}6363\ \text{Å}. \tag{III.62}$$
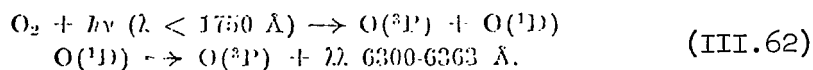
However, the intensity variation of these radiations was successfully observed as a function of the altitude, and from these observations it follows (Ref. 59) that the intensity maximum (at middle latitudes) appears at an altitude of 105-110 km. Starting from these quantitative data, and knowing both the mechanisms of dissociation and recombination of oxygen and the mechanisms of excitation of the radiations of oxygen, we are going to determine the altitude of the phenomena which affect the decomposition of O_2, and hence, deduce the structure of the upper atmosphere.

5. Determination of the altitudes

Let us consider a simple distribution given by equation (III.38) in the region of dissociation of O_2. For the different constituents of oxygen, which we shall treat as a third body (M), we write

$$N(M) = N_0(M) \, e^{-z/h} \qquad (III.63)$$

where h is the rate of logarithmic decrease of the molecular concentration $N(M)$ at altitude z. $N_0(M)$ is the molecular concentration at altitude $z = 0$, considered as the starting level.

For O_2, the vertical distribution will be necessarily different; we write, by virtue of (III.38),

$$N(O_2) = N_0(O_2) \, e^{-z/h_1} \qquad (III.64)$$

where $h_1 < h$, since, because of the dissociation, molecular oxygen decreases more rapidly with altitude than do the other constituents.

By virtue of equations (III.63 and 64), the general relation (III. 59) may be written in the form

$$N^2(O) = \frac{D_\infty N_0(O_2) \, e^{-z/h_1} \, e^{-\frac{zN_0(O_2)}{\sin h_\odot} \int_z^\infty e^{-z/h_1} dz}}{R_1 N_0(M) \, e^{-z/h} + R_2}$$

which, after integration, becomes

$$N^2(O) = \frac{D_\infty N_0(O_2) \, e^{-\left[z/h_1 + \frac{zh_1 N_0(O_2) \, e^{-z/h_1}}{\sin h_\odot} \right]}}{R_1 N_0(M) \, e^{-z/h} + R_2} \qquad (III.65)$$

This expression (III.65) gives the value of the concentration of atomic oxygen.

The dissociation number per cm^3 per second is given by relation (III.43) which, on the basis of (III.64) and after integration, is written as

$$N(O_2)D = D_{co} N_o(O_2) e^{-\left[z/h_1 + \frac{\varkappa h_1 N_o(O_2) e^{-z/h_1}}{\sin h_\odot} \right]} \qquad \text{(III.66)}$$

In order to determine the vertical distribution of the emission of the forbidden red doublet of oxygen at twilight, we must first consider

the various processes of deexcitation of the ^1D atom produced by the

photodissociation of O_2 (III.62). The radiative emission, ^1D-^3P, whose

vertical intensity distribution we are seeking, is offset by the deexcitation by collisions, whose probability is a function of the number of collisions. Let A_{21} be the probability of spontaneous emission, b_{21}

the probability of molecular formation in the Schumann-Runge system, and $a_{21} = \Omega N(M)$ the probability of deactivating collisions where Ω is pro-

portional to the effective collision cross section. The intensity of the emission will therefore be expressed as a function of the dissociation number and of the ratio of the probability of spontaneous emission to the total probability of the various initial processes of the state

^1D. We thus obtain, for the number of emissions I of $\lambda\lambda$ 6,300-6,364 Å, the expression

$$I(6300 - 6363) = \frac{N(O^2) D A_{21}}{a_{21} + b_{21} + A_{21}} \qquad \text{(III.67)}$$

$A_{21} < a_{21} + b_{21}$ may be neglected in the denominator (Ref. 60); in addi-

tion, b_{21} and a_{21} correspond to double and triple collisions, i.e., to

R_2 and $R_1 N(M)$, respectively, in equation (III.65). Hence, after inte-

grating, we write (III.67), on the basis of (III.64)

$$I(6300 - 6363) = \frac{N_o(O_2)D_{co} A_{21} e^{-\left[z/h_1 + \frac{\varkappa h_1 N_o(O_2) e^{-z/h_1}}{\sin h_\odot} \right]}}{b_{21} + \Omega N_o(M) e^{-z/h}} \qquad \text{(III.68)}$$

By differentiating relations (III.65, 66 and 68) with respect to z, we can obtain the expressions of the conditions for the maxima of the concentration of atomic oxygen, of the dissociation of O_2, and of the

intensity of the red lines of oxygen. Since the altitude of the maximum intensity of these radiations is known at middle latitudes from observations, one should be able to determine the altitudes of the other phenomena.

A priori, two cases may arise depending upon the relative importance of the two terms in the denominator in formulas (III.65 and 68). Suppose first that the effect of double collisions is negligible compared to that of triple collisions. By setting $h = w\, h_1$, where $w > 1$,

expressions (III.65 and 68) can be written, to the accepted approximation,

$$N(O) = \left[\frac{D_{c_0}N_0(O_2)}{R_1 N_0(M)}\right]^{1/2} e^{-1/2\left[\frac{w-1}{w}\frac{z}{h_1} + \frac{z h_1 N_0(O_2)\,e^{-z/h_1}}{\sin h_\odot}\right]} \quad \text{(III.69)}$$

and

$$I(6300 - 6363) = \frac{N_0(O_2)D_{c_0}A_{21}}{\Omega N_0(M)} e^{-\left[\frac{w-1}{w}\frac{z}{h_1} + \frac{z h_1 N_0(O_2)\,e^{-z/h_1}}{\sin h_\odot}\right]} \quad \text{(III.70)}$$

Cancellation of the derivative with respect to z in the expressions (III.69 and 70) gives

$$\frac{z h_1 N_0(O_2)\,e^{-z/h_1}}{\sin h_\odot} = \frac{w-1}{w} \quad \text{(III.71)}$$

If the effect of triple collisions is negligible compared to that of double collisions, (III.65 and 68) are written to the accepted approximation,

$$N(O) = \left[\frac{D_{c_0}N_0(O_2)}{R_2}\right]^{1/2} e^{-1/2\left[\frac{z}{h_1} + \frac{z h_1 N_0(O_2)\,e^{-z/h_1}}{\sin h_\odot}\right]} \quad \text{(III.72)}$$

and

$$I(6300 - 6363) = \frac{N_0(O_2)D_{c_0}A_{21}}{b_{21}} e^{-\left[\frac{z}{h_1} + \frac{z h_1 N_0(O_2)\,e^{-z/h_1}}{\sin h_\odot}\right]} \quad \text{(III.73)}$$

Cancellation of the derivative of (III.72 and 73) with respect to z yields the expression

$$\frac{z h_1 N_0(O_2) \ c^{-z/h_1}}{\sin h_\odot} = 1 \tag{III.74}$$

Finally, expression (III.66), differentiated in the same manner, yields, by cancellation

$$\frac{z h_1 N_0(O_2) \ c^{-z/h_1}}{\sin h_\odot} = 1 \tag{III.75}$$

In the end, we find the following results:

(1) In the case where triple collisions play the principal part, expressions (III.71 and 75) derived from (III.65, 66, and 67) make it possible to write the relation between the altitudes of the maxima[1]

$$\boxed{z(O)_{max} = z(6300 - 6363)_{max} = z(O_2 \longrightarrow O + O)_{max} + h_1 \log_e \frac{w - 1}{w}} \tag{III.76}$$

(2) In the case where double collisions play the principal part, expressions (III.74 and 75), also derived from (III.65, 66, and 67), yield the relation

$$z(O)_{max} = z(6300 - 6363)_{max} = z(O_2 \longrightarrow O + O)_{max} \tag{III.77}$$

Using numerical data, we shall easily deduce that relation (III.76) alone applies. Indeed, observations indicate that

$$z(6300 - 6363)_{max} = 105 \text{ to } 110 \text{ km} \tag{III.78}$$

altitude at which $N(M) > 10^{12}$. From the numerical values of the two terms in the denominator of (III.59) we deduce that, with $\zeta < 10^{-6}$,

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[1]The same result is obtained if a simple resonance effect is considered.

$$R_1 \ N(M) > R_2 \hspace{3cm} (III.79)$$

when $N(M) > 10^{12}$.

Thus, the simple relation (III.76) enables us to determine the properties characteristic of the upper atmosphere on the basis of the altitude deduced from the observations, from the maximum emission of the red lines at twilight, and without the use of any hypothesis on the structure of the atmosphere. We have seen in Chapter I that the altitude of the E region was between 100 and 130 km. This region corresponds, therefore, to the maximum dissociation of O_2, whereas the F_1 and F_2 regions, located at altitudes in excess of 200 km, are beyond the atmospheric range of this molecule. In the final analysis, the processes of decomposition and recombination affecting the O_2 molecule may have an effect on the behavior of the other constituents. This behavior will be studied in the following section.

B. Dissociation of N_2 and Formation of NO

From the presence of radiations of atomic nitrogen in the auroral spectrum, we should conclude that the N_2 molecule decomposes in the upper atomsphere. However, observation (Ref. 61) of molecular bands of N_2^+ in sunlit auroras up to altitudes of 1,000 km indicates that this compound is only partly dissociated. Although it is possible to give a rough explanation of the increase with altitude in the radiations of atomic nitrogen (Ref. 62) and molecular nitrogen (Ref. 63) (Vegard-Kaplan bands), it follows, nevertheless, that the problem of the simultaneous existence of the atom and molecule in the entire region of the upper atmosphere has not been solved. However, the knowledge of the structure of the ionosphere requires a determination of the state of dissociation of N_2. As is amply indicated by the spectroscopic data on N_2 (shape of the potential energy curves), we must not consider the possibility of photodissociation, as in the case of O_2. Moreover, a photochemical decomposition effect would contradict the presence of N_2 molecules up to 1,000 km. The simultaneous presence of N and N_2 should, therefore, result from the equilibrium of the elementary mechanisms within the upper

atmosphere. To this end, let us consider, in the transition region $(O_2 \rightarrow O + O)$ determined by the study made in the preceding section, the elementary mechanisms which are necessarily involved in the formation and decomposition of O_2.

When we have a recombination of oxygen via triple collisions according to the equation

$$O(^3P) + O(^3P) + M \rightarrow O_2 + M \qquad \text{(III.80)}$$

we also have

$$O(^3P) + N_2 + M \rightarrow N_2O + M \qquad \text{(III.81)}$$
$$O(^3P) + O_2 + M \rightarrow O_3 + M \qquad \text{(III.82)}$$
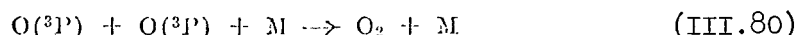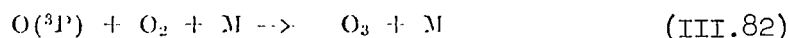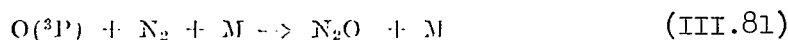
where the recombination coefficient is of the order of $4 \cdot 10^{-32}$ N(M).

In addition, we shall see later, in a study of the ionospheric properties, that the negative ions O^- exist in the upper atmosphere. Hence (see Chapter IV),

$$O^- + O \rightarrow O_2 + \varepsilon \qquad \text{(III.83)}$$
$$O^- + O_2 \rightarrow O_3 + \varepsilon \qquad \text{(III.84)}$$
$$O^- + N_2 \rightarrow N_2O + \varepsilon \qquad \text{(III.85)}$$
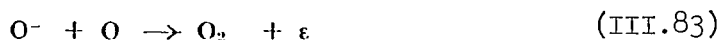
where ε represents the detached electron and where the recombination coefficient is of the order of $2 \cdot 10^{-16}$.

The three molecules O_2, O_3 and N_2O which result from (III.80 through 85) undergo photodissociation. O_2 is decomposed, as was indicated above, whereas O_3 has a very short lifetime (Ref. 64) at these altitudes. As far as N_2O is concerned, in the presence of solar radiation $\lambda < 2,140 \pm 130$ Å, a photochemical decomposition will be observed (Ref. 65) according to the equation

$$NO_2 + h\nu \rightarrow NO(^2\Pi) + N(^2D) \tag{III.86}$$
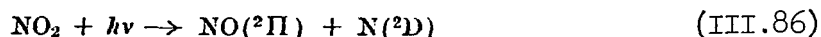
i.e., the formation of NO and N.

The presence of N results in the processes

$$N + O_2 + M \rightarrow NO_2 + M \tag{III.87}$$

$$N + O + M \rightarrow NO + M \tag{III.88}$$

$$N + N + M \rightarrow N_2 + M \tag{III.89}$$

$$N + O^- \rightarrow NO + \varepsilon \tag{III.90}$$

$$N(^4S) + N(^2D) \rightarrow N_2 + h\nu \tag{III.91}$$
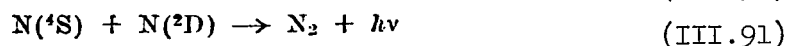
Since NO_2 undergoes a photochemical decomposition,

$$NO_2 + h\nu \; (\lambda < 4040 \,\text{Å}) \rightarrow NO + O(^3P) \tag{III.92}$$

$$NO_2 + h\nu \; (\lambda < 2459 \,\text{Å}) \rightarrow NO + O(^1D) \tag{III.93}$$
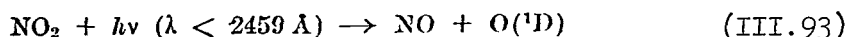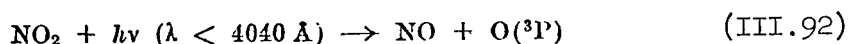
we have, from (III.88 through 93), the recombination of nitrogen and the formation of NO.

From this sequence of reactions, corresponding to the most important processes which must necessarily exist in the atmosphere starting from the formation of atomic oxygen, we deduce that NO is formed continuously in the upper atmosphere. Furthermore, no mechanism allows the direct dissociation of NO. The photochemical decomposition, which readily dissociates O_2, does not take place in the case of NO. This molecule necessarily will be ionized by the solar radiation. Indeed, from the experimental results now available (Ref. 66), we deduce that

$$NO + h\nu \; (\lambda < 1300 \pm 15 \,\text{Å}) \rightarrow NO^+ + \varepsilon \tag{III.94}$$
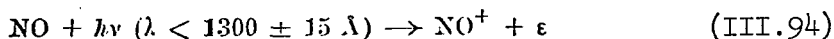
where the energy necessary for the ionization is equal to 9.5 ± 0.1 eV. In addition, since the dissociation potential of NO^+ is equal to 9.37 ± 0.2 eV, we write

$$NO^+ + h\nu \; (\lambda < 1312 \pm 25 \,\text{Å}) \rightarrow N + O^+ \tag{III.95}$$
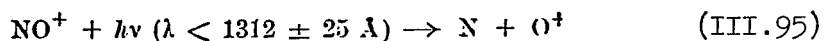
Hence, the NO molecule formed in the upper atmosphere disappears via the process of photoionization.

In order to precisely determine the atmospheric region where an equilibrium between the effects of solar radiation and the molecular formation maintains the greatest abundance of NO, it would be necessary to know the exact values of the absorption coefficients of NO and NO^+. In the absence of any experimental determination and because of the impossibility of a theoretical investigation, we must assume that the spectral region is located between the continua of photodissociation and photoionization of O_2 (see Figure 15) and includes the L_α radiation of hydrogen. Consequently, we can assert (since the absorption coefficients can differ only within certain limits) that the distribution of NO in the neutral and ionized state will not differ much from that of O_2. In other words, when we assume that O_2 is practically dissociated, we are certain that NO has been ionized to form N and O^+. Moreover, in the transition zone located under 105 km, where we have found that O and O_2 are simultaneously present and where O has not yet reached its maximum abundance, there exists an equilibrium between the production of NO and its disappearance via photoionization.

When NO disappears after its formation by either one of mechanisms (III.86 or 95), a nitrogen atom is formed. It follows that the NO and and N constituents are mutually exclusive. In the atmospheric region where recombination via triple collisions is predominant, the abundance of NO is greater than that of N. As soon as the photochemical action of NO assumes an increasingly greater importance and the triple-collision recombinations are more numerous, the number of nitrogen atoms increases. Finally, when processes such as (III.90 to 91) acquire a relative importance, the abundance of NO becomes insignificant as a result of the effect of the processes (III.92 and 93), as compared with the abundance of N, which is limited only by the molecular recombination to N_2.

In short, NO characterizes the atmospheric region located below the maximum of dissociation of O_2, whereas N becomes important at the altitude (105-110 km at our latitudes) of the maximum of abundance of O.

The results acquired thus far provide the essential indication that the composition of the upper atmosphere is different from that of the lower and middle atmosphere. The permanently present O_2 and N_2 are replaced by O and partially by N, whereas NO is formed in the transition

zone. On the other hand, if we draw a parallel between this behavior and the observational data on the altitude of the ionospheric regions, we may conclude that NO and O_2 characterize solely the atmospheric re-

gion of the E layer, whereas the other constituents, O, N and N_2 are present in the region of the F_1 and F_2 layers.

C. Helium

That oxygen and atomic nitrogen characterize the atmosphere at the highest altitudes is well demonstrated by the investigations made in the preceding sections. However, if we apply the equation of statics (III.13) to the upper atmosphere, the vertical distribution of the molecular concentration should be subjected to a higher temperature so that the density may still be sufficient at the highest altitudes. Even in this case, the diffusion phenomenon could not exist, or else the atmospheric region located above 300 km would be exclusively made up of atoms and the N_2 molecule would be absent. Taking the ionospheric re-

sults into consideration, radio engineers have advanced the hypothesis that the vertical molecular distribution is subjected to a high temperature (Ref. 67), in order to make the calculated altitudes of the F_1 and

F_2 regions agree with the experimental determinations. Thus, by implic-

itly assuming that the rate h of logarithmic decrease of the molecular concentration with altitude (III.38) is identical to the height H of the homogeneous atmosphere (III.39), one still assumes that the temperatures of the E and F regions are quite different. Whereas, for the E region, the assumed value of H (which we shall call the ionospheric height scale) is of the order of 10 km, it reaches or surpasses 30 km for the F region. In the case of a uniform composition, we see that the temperature of $375^{\circ}K$ at about 100 km should exceed $700^{\circ}K$ at about 250 km.

For this hypothesis to be acceptable, it must be able to interpret the observational data of all the stations. Thus, at the stations of the auroral zone (Tromsö, for example), the E and F regions are analogous to the regions of middle latitudes, so that the ionospheric scales of height H do not show any essential differences. We have recently indicated (Ref. 68) that the region of the upper atmosphere at middle latitudes is subjected to a solar effect which is more pronounced than that to which the polar regions are subjected during winter, and its temperature is therefore slightly higher. However, we have also shown (Ref. 68) that the temperature of the auroral region at about 100 km was below $0^{\circ}C$. In addition, observations made by Vegard (Ref. 69) have never shown the

temperature increase required by the above hypothesis. Hence, it is impossible to reconcile the low "auroral temperatures" (Ref. 68), whose determination ultimately depends on the observation, with the "ionospheric temperatures" (Ref. 68).

Consequently, it is our view that the results of the theory and observation contradict a marked increase of the temperature with the altitude.

Since the hypothesis of an elevated temperature in the F_2 region cannot be accepted, only the decrease in the average molecular mass, by virtue of (III.9), should be one of the principal causes of this extension of the atmosphere toward high altitudes. We have seen that the total dissociation of O_2 and partial dissociation of N_2 takes place between the E anf F regions. However, a simple calculation shows that this dissociation accounts only partially for the change in the structure of the atmosphere expressed by the variation of H. Hence, the general decrease of the average molecular mass should be attributed to a lightweight element which has special properties within the atmosphere. This element should be abundant, so that the average molecular mass be appreciably influenced by its presence. Furthermore, its power of molecular association should be negligible as compared to O_2 and N_2. Moreover,

its spectroscopic properties must be such that its lines are difficult to observe in the spectrum of the light of the night sky and even in the spectrum of the auroras. In addition, the difference in the ionospheric height scale of the E and F regions should be justified in the presence of this element.

Only one atom meets all the conditions which we have just enumerated: helium. Indeed, this inert gas does not enter into any molecular association. Its electronic affinity is null. No forbidden transition (the most intense radiations in the spectra of the night sky and of the aurora) is located in the observable spectral range. The radiations which may appear in this range correspond to allowed transitions. The example of the oxygen atom (Ref. 70) shows that the intensity of the allowed lines is very weak as compared to the intensity of the forbidden lines, and the allowed transitions of HeI, whose excitation potentials exceed those of OI, will therefore have, a priori, a very weak intensity. Hence, their observation even for an abundance of HeI equal to that of OI will be exceptional (Ref. 71).[1]

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[1]The lines of the hydrogen series have been observed only very recently in the spectrum of auroras (L. Vegard, Ref. 71).

Let us assume the effective presence of helium. Then, we only have to account for the difference in the ionospheric height scales of the E and F regions. A priori, two explanations may be considered: the first is to assume that the influence of helium becomes effective only at the level of the F region; the second is that the ionospheric height scales do not correspond to these heights of the homogeneous atmosphere H but, in reality, to the parameter h of the vertical distribution of the ionospheric constituent subjected to ionization. In the first case, it is difficult to find the physical reason for an accumulation of helium starting at 200 km, and this explanation cannot be retained. On the contrary, if it is assumed that the parameter h representing the rate of logarithmic decrease of the constituent forming the E region applies to a molecule such as O_2, it is possible to assume that h is smaller

than the H scale attributable to the other constituents O, N_2, etc. and

it will be possible to consider helium as a permanent element of the upper atmosphere.

In short, helium should be added to the principal constituents O_2,

NO, N_2, O and N, which effectively determine the average molecular mass of the upper atmosphere. However, we still have to interpret the constant of the ionospheric height scale in order to explain the difference between the scales of the E and F regions. This point will be elucidated in Section 3, of Chapter V.

CHAPTER IV.   GENERAL IONIZATION EQUATIONS

Section 1.   Introduction

The determination of the state of ionization in the upper atmos-
phere requires an a priori knowledge of the elementary mechanisms affect-
ing the distribution of the physical constituents--neutral molecules
and atoms, positive and negative ions, and electrons.   Indeed, we cannot
consider the simple case of thermal ionization determined by the Saha
equation, since the atmosphere is not made up of a gas of uniform tem-
perature subjected to its own temperature radiation.   In other words,
the use of an equation resulting from a simple chemical reaction is not
permitted because the statistical equilibrium does not correspond to the
radiative equilibrium.

In fact, the atmospheric gases are subjected to the action of an
external field of radiations emanating from the sun, and the knowledge
of·the elementary processes such as photoionization and cumulative ioni-
zation is required for the determination of the production of charged
particles.   In the absence of solar radiation (night conditions), ioniza-
tion due to either electron impact and/or collisions of positive ions
could be involved.   However, these processes, which require an excessive-
ly high energy, are always negligible in the presence of ionizations
resulting from a transfer of activation by collisions of the second kind.
Moreover, since the concentration of excited particles is relatively
slight, the latter collisions will not be considered in the presence of
the ionization residue induced during the day in the field of the solar
radiation.

The radiative processes of ionization of neutral particles and
negative ions are offset by the processes of spontaneous recombination
which depend on the physical conditions of the atmosphere.   As in the
case of ionization, one must resort to the elementary mechanisms result-
ing from collisions between neutral particles, ions and electrons.   How-
ever, there is a fundamental difference between the processes inducing
the ionization and recombination, respectively, because of the differ-
ence in the temperature of the gas (atmosphere) and that of the source
(sun).   Ionization can appear only under normal state conditions, where-
as recombination takes place in all of the normal and excited states.
In other words, we are dealing in the atmosphere with a gas whose tem-
perature is too low, relative to the equivalent temperature of the solar

radiation, to permit a state of equilibrium in which the transitions
from a given quantum state are solely offset by transitions to the same
state. It is, therefore, necessary to determine the state of ionization
in its most general form and to find adequate equations for direct appli-
cation to the ionosphere.

Section 2. General Equations

Let us consider at time t a medium composed of $N_j = N_j$ (t) neutral

atoms of the j species of $N_j^+ = N_j^+$ (t) positive ions, of $N_j^- = N_j^-$ (t)

negative ions, and of $N_E = N_E$ (t) electrons per cm^3. In general terms

we can consider the relations

$$\frac{\partial N_E}{\partial t} = \sum_k i_k N_k + \sum_k d_k N_k^- + \sum_k p_k N_k^- N_k - \sum_k r_k N_k^+ N_E - \sum_k a_k N_k N_E \qquad (IV.1)$$

$$\frac{\partial N_j^+}{\partial t} = i_j N_j - r_j N_j^+ N_E - N_j^+ \sum_k f_k N_k^- \qquad (IV.2)$$

$$\frac{\partial N_j^-}{\partial t} = a_j N_j N_E - d_j N_j^- - N_j^- \sum_k p_k N_k - N_j^- \sum_k f_k N_k^+ \qquad (IV.3)$$

$$(j,\ k = 1,2...)$$

where we have taken into account the following elementary processes:

(1) for relation (1), appearance of electrons via:

(a) photoelectric ionization whose coefficient is i_k

(b) photoelectric detachment of electrons from negative ions,
coefficient d_k

(c) molecular production (radiative or via triple collisions)
from negative ions and neutral atoms, coefficient p_k

and disappearance of electrons via:

(a) recombination of electrons and positive ions, coefficient r_k

(b) attachment of electrons to neutral atoms or molecules, coef-
ficient a_k

(2) for relation (2), appearance of positive ions via:

photoelectric ionization, coefficient i_j

and disappearance of positive ions via:

(a) recombination of positive ions and electrons, coefficient r_j

(b) formation of neutral molecules or atoms from positive and negative ions, coefficient f_k

(3) for relation (3), appearance of negative ions via:

attachment of an electron to an atom or to a neutral molecule, coefficient a_j

and disappearance of negative ions via:

(a) photoelectric detachment of the electrons of negative ions, coefficient d_j

(b) molecular production from negative ions and neutral atoms, coefficient p_k

(c) formation of molecules or neutral atoms from negative and positive ions, coefficient f_k

These equations being formulated, we now have to find the values of the various coefficients. To this end, we shall successively study the different cases which may present themselves and thus establish the relations which will be immediately applicable to the ionosphere.

In order to simplify the notation, we shall determine the coefficients separately for each species j of atoms. Thus, we shall be able to apply the calculated values immediately to equations (V.1, 2 and 3) adapted to a single element.

$$\frac{\partial N_E}{\partial t} = i_j \, N_j + d N_j + p_j \, N_j^- N_j - r_j \, N_j^+ N_E - a_j \, N_j \, N_E \qquad \text{(IV.4)}$$

$$\frac{\partial N_j^+}{\partial t} = i_j \, N_j - r_j \, N_j^+ N_E - f_j \, N_j^+ N_j^- \qquad \text{(IV.5)}$$

$$\frac{\partial N_j^-}{\partial t} = a_j \, N_j \, N_E - d_j \, N_j^- - p_j \, N_j^- N_j - f_j \, N_j^+ N_j^- \qquad \text{(IV.6)}$$

Section 3. Coefficients Determinations

We are still considering a medium composed of atoms of different species, in particular, of N_j atoms of species j, and of N_E electrons per cm^3, whose temperature T_E characterizes the Maxwellian velocity of the electrons. This medium will also contain positive ions N^+ and negative ions N^-. The gas is located in a radiation field corresponding to the diluted radiation of the sun. The density of the radiation will be given (see Chapter II) by that of a black body of temperature T_S ($\lambda > 910$ Å) multiplied by the geometrical dilution factor $\beta_S = 5.4 \cdot 10^{-6}$, or by the density of a black body of temperature T_{SE} ($\lambda < 910$ Å) multiplied by the dilution factor $\beta_{SE} = 1.06 \cdot 10^{-12}$. The numbers of quanta reaching the top of the atmosphere are deduced for these two cases, respectively, from relations (II.2) and (II.39) determined during the investigation of the energy of solar radiation carried out in Chapter II.

A. Electron Production

Case 1. <u>Photoionization</u>, coefficient i.

Let us consider atoms of species j susceptible of being ionized at an altitude z in the atmosphere. The radiations emitted by the sun will undergo an absorption before arriving at the point where we are studying the photoionization. Let $\tau(v)$ be the optical thickness for a frequency v, defined by the relation

$$d\tau(v) = \frac{N_j \varkappa_j(v)\,dz}{\sin h_\odot} \tag{IV.7}$$

where N_j is the number of atoms per cm^3, $\varkappa(v)$ the coefficient of atomic absorption, and $\sin h_\odot$ the sine of the angle of height of the sun above the horizon. We shall, therefore, write that the number of processes of absorption inducing ionization in the medium of species j, located at an altitude z in the atmosphere, is

$$N_j i = N_j\, i_\infty\, e^{-\tau} \tag{IV.8}$$

where i_∞ is the ionization coefficient at the top of the atmosphere, or

better, at an altitude at which the absorption no longer plays any part. The atoms of species j will be ionized when acted upon by an absorbed energy, hv, which is greater than $hv_{o,j}$, the ionization potential. The

excess energy $h(v-v_{o,j})$ will be converted into the translational energy of the electron

$$1/2 \ mv^2 = h(v-v_{o,j}) \qquad (IV.9)$$

In order to calculate the number of absorption processes inducing the ionization of atoms of species j, we must know the probability of absorption from the normal state of the neutral atom to the ionized atom. Assuming this value to be known, in the case where there is no absorption between the source and the point considered, we can express

the number of photoionizations per cm³ per second for the atoms N_j in a frequency interval dv by

$$N_j \ \frac{\partial B_j}{\partial v} \ \beta\varrho(v)dv \qquad (IV.10)$$

where $\delta B_j/\delta v$ is the probability of photoionization of the solar radiation at the point under consideration.

In the frequency interval $v = \infty - v_{o,j}$, the number of ionization processes is equal to

$$N_j \ i_\infty = N_j \int_{v_{o\,j}}^{\infty} \frac{\partial B_j}{\partial v} \ \beta\varrho(v)dv$$

or, from (II.1),

$$N_j \ i_\infty = \frac{N_j 8\pi h\beta}{c^3} \int_{v_{o,j}}^{\infty} \frac{\partial B_j}{\partial v} \ \frac{v^3 dv}{e^{hv/kT}-1} \qquad (IV.11)$$

Introducing the atomic absorption coefficient

$$\varkappa_j(v) = \frac{hv}{c} \frac{\partial B_j}{\partial v} \qquad (IV.12)$$

we write equation (IV.11) as

$$N_j\, i_\infty = \frac{N_j 8\pi\beta}{c^2} \int_{v_{0,j}}^{\infty} \frac{v^2 \varkappa_j(v)\,dv}{e^{\,h v/kT} - 1} \qquad (IV.13)$$

In order to integrate this expression (IV.13), we must know the law of variation of the coefficient $\varkappa_j(v)$ as a function of the frequency.

In the case of a hydrogenlike atom,

$$\varkappa_j(v) = \text{constant} \cdot v^{-3} = C_j \cdot v^{-3} \qquad (IV.14)$$

For the states ^{1}S and ^{3}S of helium, we have

$$\varkappa_j(v) = \text{constant} \cdot v^{-2} = C_j \cdot v^{-2} \qquad (IV.15)$$

For the normal state of the nitrogen atom,

$$\varkappa_j(v) = \text{constant} \cdot v^{-1} = C_j \cdot v^{-1} \qquad (IV.16)$$

In the other cases where the distribution of the absorption is known and where it is impossible to determine a simple law, an average value of $\varkappa_j$ may be taken.

If $\varkappa_j(v) = C_j \cdot v^{-3}$, equation (IV.13) is written as

$$N_j\, i_\infty = \frac{8\pi\beta}{c^2} N_j C_j \int_{v_{0,j}}^{\infty} \frac{dv}{v(e^{\,h v/kT} - 1)} \qquad (IV.17)$$

In order to calculate conveniently the integral defined in the second member, let us set

$$Ei\,(x_1) \equiv \int_{x_1}^{\infty} \frac{e^{-x}\,dx}{x} \quad \text{et} \quad Ei\,(\mu x_1) \equiv \int_{x_1}^{\infty} \frac{e^{-\mu x}\,dx}{x}$$

By expanding $(e^x - 1)^{-1}$ in series, we find

$$(e^x - 1)^{-1} = e^{-x}(1 + e^{-x} + e^{-2x} + \dots)$$

and the integrated expression (IV.17) is written, after setting $hv_{o,j}/kT \equiv x$, as

$$i_\infty \equiv \frac{8\pi\beta}{c^2} C_j \sum_{\mu=1}^{\infty} \mathrm{E}i\,(\mu\,\frac{hv_{o,j}}{kT}) \qquad \text{(IV.18)}$$

If $\varkappa_j(v) = C_j \cdot v^{-2}$, we write (IV.13) in the form

$$N_j\,i_\infty = \frac{8\pi\beta}{c^2}\,N_j C_j \int_{v_{o,j}}^{\infty} \frac{dv}{e^{\,hv/kT}-1}$$

where

$$N_j\,i_\infty = \frac{8\pi\beta}{c^2}\,\frac{kT}{h}\,N_j C_j \int_{hv_{o,j}/kT}^{\infty} \frac{dx}{e^x - 1}$$

Whence, by integrating

$$i_\infty = \frac{8\pi\beta}{c^2}\,\frac{kT}{h}\,C_j\,log_e\,(1 - e^{-\,hv_{o,j}/kT}) \qquad \text{(IV.19)}$$

If $\varkappa_j(v) = C_j \cdot v^{-1}$, we obtain the following formula for (IV.13)

$$N_j\,i_\infty = \frac{8\pi\beta}{c^2}\,N_j C_j \int_{v_{o,j}}^{\infty} \frac{v\,dv}{e^{\,hv/kT} - 1}$$

or

$$N_j \, i_\infty = \frac{8\pi\beta}{c^2} \left(\frac{kT}{h}\right)^2 N_j C_j \int_{h\nu_{o,j}/kT}^\infty \frac{x\,dx}{e^x - 1}$$

By exapnding $(e^x - 1)^{-1}$ in series, we find

$$\int_{h\nu_{o,j}/kT}^\infty x(e^x - 1)^{-1}\,dx = \sum_{w=1}^\infty \frac{1}{w} e^{-wh\nu_{o,j}/kT} \left(\frac{h\nu_{o,j}}{kT} + \frac{1}{w}\right);$$

whence

$$i_x = \frac{8\pi\beta}{c^2} \left(\frac{kT}{h}\right)^2 C_j \sum_{w=1}^\infty \frac{1}{w} e^{-wh\nu_{o,j}/kT} \left(\frac{h\nu_{o,j}}{kT} + \frac{1}{w}\right) \qquad (IV.20)$$

Finally, if we take an average value κ of $\kappa_j(v)$, we write (IV.13) as

$$N_j \, i_\infty = \frac{8\pi\beta}{c^2} N_j \kappa \int_{\nu_{o,j}}^\infty \frac{\nu^2 d\nu}{e^{h\nu/kT} - 1}$$

where

$$N_j \, i_\infty = \frac{8\pi\beta}{c^2} \left(\frac{kT}{h}\right)^3 \kappa \int_{h\nu_{o,}/kT}^\infty \frac{x^2 dx}{e^x - 1}$$

We see that if we take (II.2) into account, we have

$$i_\infty = \kappa Q \qquad (IV.21)$$

where Q is the number of quanta reaching the top of the atmosphere.

In short, expressions (IV.18, 19, 20 and 21) provide the values of the ionization coefficient, and thus the number of ionized atoms of a given species j per second per cm^3 as a function of the temperature T of the sun, in the case where there is no absorption between the source and the point under consideration.

In the case of absorption, we have, by virtue of (IV.8),

$$i = i_\infty \, e^{-\tau}$$

where τ is given, on the basis of (IV.7), by

$$\tau = \frac{\varkappa}{\sin h_\odot} \int_z^\infty N dz = \frac{\varkappa h N}{\sin h_\odot}$$

where $N = N_0 e^{-z/h}$ (cf. III.38).

Whence, finally

$$\boxed{i = i_\infty e^{-\dfrac{\varkappa h N}{\sin h_\odot}}} \tag{IV.22}$$

Applications

Oxygen molecule

(1) $O_2 + h\nu \, (\lambda < 765 \text{ Å}) \longrightarrow O_2^+ + \varepsilon$ (electron).
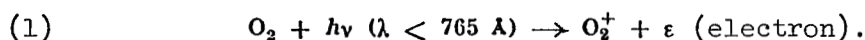
Observation of Price and Collins (Phys. Rev., 48, 714, 1935); coefficient of absorption $\varkappa = 1.72 \cdot 10^{-17}$ to $3.44 \cdot 10^{-18}$, calculated by Bhar (Indian J. of Phys., 12,363, 1938). This case will not be considered, since the usable solar energy has been absorbed by O and N in the upper layers (see Chapter V).

(2) $O_2 + h\nu \, (\lambda < 1019 \text{ Å}) \longrightarrow O_2^+ + \varepsilon.$
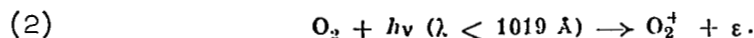
Weak absorption, not yet observed, for which Mitra, Bhar and Ghosh (Indian J. of Phys., 12, 455, 1958) have chosen $x = 10^{-21}$.

(3) $\qquad O_2 + h\nu \; (1000 \text{ Å} < \lambda < 910 \text{ Å}) \longrightarrow O_2 \longrightarrow O_2^+ + \varepsilon.$
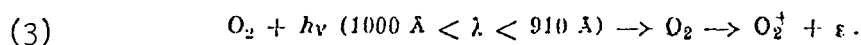
System of bands which, beginning at 1,019 Å, are in the preioniza-tion region. The absorption of these bands is five times greater than in the dissociation continuum at λ 1,750 Å. x is then assumed to be $4 \cdot 10^{-17}$.

For the oxygen molecule, we apply relation (IV.21) and obtain (see Table 1)

$$i_\infty \; (\lambda < 1{,}019 \text{ Å}) = 10^{-21} \cdot Q = 10^{-11} \text{ if } T_S = 6{,}000^\circ K \qquad (\text{IV}.23)$$

$$i_\infty \; (1000 < \lambda < 910 \text{ Å}) = 4 \cdot 10^{-17} \cdot Q = \begin{matrix} 2.8 \cdot 10^{-7} \text{ if } T_S = 6{,}000^\circ K \\ 7.2 \cdot 10^{-8} \text{ if } T_S = 5{,}740^\circ K \end{matrix} \qquad (\text{IV}.24)$$

NOTE. The hydrogen lines L_γ (λ 972.55 Å) and L_ξ (λ 930.76 Å) are absorbed by the preionization bands of O_2 observed by Takamine and Suga (Scient. Papers Inst. Phys. Chem. Res., 29, 213, 1936).

Nitrogen molecule

(1) $\qquad N_2 + h\nu \; (\lambda < 661 \text{ Å}) \longrightarrow N_2^+ + \varepsilon.$
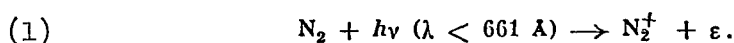
Observation of Hopfield (Phys. Rev., 36, 789, 1930) and Takamine, Suga and Tanaka (Scient. Papers Inst. Phys. Chem. Res., 34, 843, 1938). A few tenths of one mm at standard pressure indicate the absorption of the continuum. Bhar (Indian J. of Phys., 12, 363, 1938) assumes that $x = 9.67 \cdot 10^{-18}$ or $1.94 \cdot 10^{-18}$. See Wulf and Deming (Terr. Magn., 43, 283, 1938). x may then be assumed to be 10^{-17} cm^2.

(2) $\qquad$ $N_2 + h\nu \ (\lambda < 795 \ \text{Å}) \rightarrow N_2^+ + \varepsilon.$
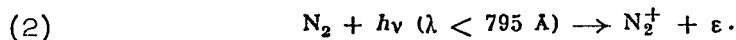
Absorption observed by Worley and Jenkins (Phys. Rev., 54, 305, 1938) which appears weaker than that of the preceding continuum. In this case, $\varkappa$ is assumed to be 10^{-18}.

Formula (IV. 21) is applicable where Q is provided by relation (II.39) and in Figure 11. We thus obtain

$$i_\infty \ (\lambda < 661 \ \text{Å}) = 10^{-17} \cdot 2.24 \cdot 10^7 = 2.24 \cdot 10^{-10^1} \qquad \text{(IV.25)}$$

$$i_\infty \ (\lambda < 795 \ \text{Å}) = 10^{-18} \cdot 3.4 \cdot 10^8 = 3.4 \cdot 10^{-10} \qquad \text{(IV.26)}$$

Oxygen atom

$$O + h\nu \ (\lambda < 910 \ \text{Å}) = O^+ + \varepsilon.$$
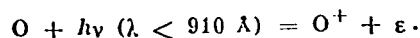
Coefficient calculated by Bates (Monthly Notices, 100, 25, 1939). $\varkappa(v_0) = 1.4 \cdot 10^{-17}$. Variation with frequency given in Figure 15. Application of relation (IV.21), where $\varkappa = 1.45 \cdot 10^{-17}$ and Q, deduced from formula (II.42) or from corresponding Figure 11, is $1.79 \cdot 10^9$, gives

$$i_\infty \ (\lambda < 910 \ \text{Å}) = 2.6 \cdot 10^{-8} \qquad \text{(IV.27)}$$

It is to be noted at this point that this value of i_∞ corresponds to the minimum of solar activity. Relation (II.39) is deduced, in the final analysis, from the observational results obtained during the eclipse of 1932. For the value during a solar activity maximum, the value of i_∞ (IV.27) may be multiplied by 3. Hence,

$$i_\infty \ (\lambda < 910 \ \text{Å}) = 7.8 \cdot 10^{-8} \qquad \text{(IV.28)}$$

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[1]It is to be noted that this continuum is in the region of λ 584 Å of helium, where $Q < 10^9$ quanta.

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Nitrogen atom

$$N + h\nu \ (\lambda < 850 \text{ Å}) = N^+ + \varepsilon.$$

Coefficient calculated by Bates (Monthly Notices, 100, 25, 1939), $\varkappa(\nu_0) = 2.8 \cdot 10^{-17}$. From the curve traced by Bates, we deduce the following law

$$\varkappa(\nu) = 7.76 \cdot 10^{-2} \cdot \nu^{-1}$$

Hence, the application of formula (IV.20) with $T = T_{SE} = 12,000^\circ K$ and $\beta_{SE} = 1.06 \cdot 10^{-12}$ gives the following results

$$i_\infty \ (\lambda < 850 \text{ Å}) = 1.6 \cdot 10^{-8} \qquad \text{(IV.29)}$$

Helium atom

For the states of helium, we deduce from the theoretical results of Vinti (Phys. Rev., 44, 524, 1933) and Goldberg (Ap. J., 90, 414, 1939) the following values of the absorption coefficients:

For the states $\begin{cases} 1^1S, \ \varkappa(\nu) \ [\lambda < 504 \text{ Å}] = 2.8 \times 10^{14} \times \nu^{-2} \\ 2^1S, \ \varkappa(\nu) \ [\lambda < 3120 \text{ Å}] = 5.48 \times 10^{12} \times \nu^{-2} \\ 2^3S, \ \varkappa(\nu) \ [\lambda < 2600 \text{ Å}] = 8.40 \times 10^{12} \times \nu^{-2} \end{cases}$

For the states $\begin{cases} 2^3P, \ \varkappa(\nu) \ [\lambda < 3421 \text{ Å}] = 2.85 \times 10^{27} \times \nu^{-3} \\ 2^1P, \ \varkappa(\nu) \ [\lambda < 3678 \text{ Å}] = 1.41 \times 10^{27} \times \nu^{-3} \end{cases}$

For the S states, relation (IV.19) applies and we have

$$i_\infty \ (\lambda < 504 \text{ Å}) = 9.7 \cdot 10^{-13} \qquad \text{(IV.30)}$$

with $T_{SE} = 12,000^\circ K$ and $\beta_{SE} = 1.06 \cdot 10^{-12}$.

If $T_S = 5,740^\circ K$ and $\beta_S = 5.4 \cdot 10^{-6}$,

$$i_\infty \ (\lambda < 3,120 \text{ Å}) = 4.93 \cdot 10^{-2} \qquad \text{(IV.31)}$$

$$i_\infty \; (\lambda < 2{,}600 \; \text{Å}) = 1.11 \cdot 10^{-2} \tag{IV.32}$$

For the P states, relation (IV.18) gives the values of i_∞

$$i_\infty \; (\lambda < 3{,}421 \; \text{Å}) = 3.44 \cdot 10^{-2} \tag{IV.33}$$

$$i_\infty \; (\lambda < 3{,}678 \; \text{Å}) = 3.06 \cdot 10^{-2} \tag{IV.34}$$

Case 2. Photodetachment, coefficient d.

The mechanism of photodetachment corresponds to the mechanism of photoionization. We can, therefore, repeat the same reasoning as that used for the derivation of equations (IV.10 ff.). We can, therefore, write

$$N^- \, d = \frac{8\pi\beta}{c^2} \, N^- \int_{\nu_{0.j}}^{\infty} \frac{\nu^2 \varkappa(\nu)\, d\nu}{e^{h\nu/kT} - 1}$$

and by integrating (cf. IV.21), after adopting an average value $\varkappa$ for $\varkappa(v)$

$$N^- \, d = N^- \, \varkappa \, Q$$

Application. In the upper atmosphere, the most abundant negative ions will be O^- and O_2^-. Unfortunately, it is impossible to determine a sufficiently accurate value of the energy of photodetachment. An approximate value may be determined in accordance with Massey (Proc. Roy. Soc. London, 163, 542, 1937). In addition, let us note that the spectrum of a negative ion has never been observed.

Case 3. Detachment by collision, coefficient p.

In the atmosphere, the detachment of electrons by collision is possible because the energy of detachment is relatively low. In his study of the mechanisms of negative ions, Massey (Negative Ions, Cambridge,

1938) points out that the detachment by collisions occurs according to the process

$$A^- + B \longrightarrow AB + \epsilon$$
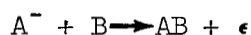
It is, therefore, necessary to determine the number $\mathfrak{N}(A^-, B)$ of double collisions (kinetic collisions) of a negative ion A^- with a neutral particle B, and to know the probability $\omega(A^-, B)$ of molecular production AB during the kinetic collision. We immediately find from (III.49)

$$p_j N^- N_j \equiv p \, N^-(A)N(B) \equiv \mathfrak{N}(A^-, B) \, \omega(A^-, B)$$

$$= N^-(A) \, N(B) \, \sqrt{8\pi\sigma_{AB}^2} \, \omega(A^-, B) \left(\frac{m_A + m_B}{m_A m_B}\right)^{1/2} (kT)^{1/2}$$

(IV.36)

Applications. Let us consider

$$O^- + O \longrightarrow O_2 + \bullet$$
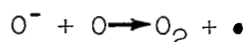
For this reaction, where $\sigma = 1.204 \cdot 10^{-8}$ cm is the molecular diameter of O_2 in the normal state and $T = 300^\circ K$, we obtain from (IV.36)

$$p = 2 \cdot 10^{-16}$$

(IV.37)

if we adopt the value given by Massey (Negative Ions, Cambridge, 1938) for $\omega(A^-, B) = 10^{-5}$.

The same conclusions apply to N and N_2.

B. Disappearance of Electrons

Case 1. Radiative recombination, coefficient r.

In order to determine the number of processes of radiative recombination, we must know the emission coefficient γ_{nj} for every quantum state n. However, there is a possibility of relating γ_{nj} with $\varkappa_{nj}$ by

considering Einstein's relations between the atomic absorption and emission applied to the continuum of the series. According to Milne (Ref. 72) and Roseland (Ref. 73), the following expression is obtained by setting $\gamma_{nj} = vq_{nj}$, where q_{nj} is the capture cross section:

$$q_{nj}(v, v_{o,nj}) = \frac{g_{nj}}{g_{cj}} \frac{2h^2\nu^2}{m^2c^2v^2} \varkappa(\nu, \nu_{o,nj}) \qquad (IV.38)$$

where q_{nj} and q_{cj} are the statistical weights of the n state and of the

continuous state for species j and where v is the velocity of the electron related to the frequency ν by relation (IV.9).

If now dN_E denotes the number of electrons (per cm^3) whose velocities are comprised between v and v + dv, we can write that the number

of recombinations η_{nj} per cm^3 per second in the n state of species j is equal to

$$\eta_{nj}(v)dv = N_j^+ \, dN_E \, vq_{nj} \left[1 + \beta_s \left(e^{h\nu/kT_s} - 1 \right)^{-1} \right] \qquad (IV.39)$$

where vq_{nj} is the coefficient of spontaneous recombination, and where

the term in brackets corresponds to the effect of the induced emission. In the atmosphere, the induced emission being negligible in the presence of the spontaneous emission, we shall disregard it below.

The number of electrons dN_E is given by the formula expressing the

law of statistical distribution

$$dN_E = 4\pi N_E \; 1/2 \left(\frac{m}{2\pi k T_E} \right)^{3/2} e^{-mv^2/2kT_E} v^2 dv \qquad (IV.40)$$

Equation (IV.39) is then written, account being taken of (IV.9, 38 and 40), as

$$\eta_{nj}(v)dv = N_j^+ N_E \frac{4\pi h^3}{c^2} \left(\frac{1}{2\pi m k T_E} \right)^{3/2} \frac{g_{nj}}{g_{cj}} \varkappa_{nj}(\nu) \; e^{-h(\nu - \nu_{o,nj})/kT_E} \nu' dv \qquad (IV.41)$$

By integrating for all the values of v, or of ν on the basis of (IV.9), and summing for all the states,

$$N_j^+ N_E\, r \;=\; \sum_{n=1}^{\infty} \int_{\nu_{o,nj}}^{\infty} \eta_{nj}(v)\, dv \tag{IV.42}$$

$$=\; N_j^+ N_E\, \frac{4\pi h^3}{c^2}\left(\frac{1}{2\pi m k T_E}\right)^{3/2} \sum_{n=1}^{\infty} e^{h\nu_{o,nj}/kT_E}\,\frac{g_{nj}}{g_{cj}}\int_{\nu_{o,nj}}^{\infty}\frac{\nu^2 \varkappa_{nj}(\nu)\; d\nu}{e^{h\nu/kT_E}}$$

In order to integrate this expression we must know the law of variation of $\varkappa(v)$.

If $\quad \varkappa_{nj}(\nu) = C_{nj} \times \nu^{-3}$, we obtain

$$\int_{\nu_{o,nj}}^{\infty}\frac{\nu^2 \varkappa_{nj}(\nu)\, d\nu}{e^{\,h\nu/kT_E}} = C_{nj}\int_{h\nu_{o,nj}/kT_E}^{\infty}\frac{e^{-x}}{x}\, dx = C_{nj}\times \mathrm{E}i\left(\frac{h\nu_{o,nj}}{kT_E}\right)$$

and expression (IV.42) is then written

$$\boxed{\;r = \frac{4\pi}{c^2}\left(\frac{h^2}{2\pi m k T_E}\right)^{3/2}\sum_{n=1}^{\infty}\frac{g_{nj}}{g_{cj}}\,C_{nj}\,\mathrm{E}i\left(\frac{h\nu_{o,nj}}{kT_E}\right)e^{h\nu_{o,nj}/kT_E}\;} \tag{IV.43}$$

If $\quad \varkappa_{nj}(\nu) = C_{nj}\times \nu^{-2}$, we similarly find

$$\int_{\nu_{o,nj}}^{\infty}\frac{\nu^2 \varkappa_{nj}(\nu)\; d\nu}{e^{h\nu/kT_E}} = \frac{C_{nj}kT_E}{h}\int_{h\nu_{o,nj}/kT_E}^{\infty}e^{-x}\, dx = C_{nj}\,\frac{kT_E}{h}\; e^{-h\nu_{o,nj}/kT_E}$$

Hence, the integrated expression (IV.42) gives the following result:

$$\boxed{\;r \;=\; \frac{\sqrt{2}\, h^2}{\sqrt{\pi c^2 m^{3/2} k^{1/2}}}\,\frac{1}{\sqrt{T_E}}\sum_{n=1}^{\infty}C_{nj}\,\frac{g_{nj}}{g_{cj}}\;} \tag{IV.44}$$

If $\varkappa_{nj}(v) = C_{nj} \times v^{-1}$, we obtain

$$\int_{v_{o,nj}}^{\infty} \frac{v^2 \varkappa_{nj}(v)\, dv}{e^{hv/kT_E}} = C_{nj}\left(\frac{kT_E}{h}\right)^2 \int_{hv_{o,nj}/kT_E}^{\infty} x e^{-x} dx = C_{nj}\left(\frac{kT_E}{h}\right)^2 \left(\frac{hv_{o,nj}}{kT_E} + 1\right) e^{-hv_{o,nj}/kT_E}$$

Hence, we write the integrated expression (IV.42) in the form

$$r = \frac{4\pi h}{c^2}\left(\frac{1}{2\pi m}\right)^{3/2}(kT_E)^{\frac{1}{2}} \sum_{n=1}^{\infty} C_{nj}\frac{g_{nj}}{g_{cj}}\left(\frac{hv_{o,nj}}{kT_E} + 1\right) \qquad \text{(IV.45)}$$

Finally, if we can apply the mean value theorem by considering a mean value $\varkappa_{nj}$ for $\varkappa_{nj}(v)$, we have

$$\int_{v_{o,nj}}^{\infty} \frac{v^2 \varkappa_{nj}(v)}{e^{hv/kT_E}} dv = \varkappa_{nj}\left(\frac{kT_E}{h}\right)^3 \int_{hv_{o,nj}/kT_E}^{\infty} x^2 e^{-x} dx$$

$$= \varkappa_{nj}\left(\frac{kT_E}{h}\right)^3 \left[\left(\frac{hv_{o,nj}}{kT_E} + 1\right)^2 + 1\right] e^{-hv_{o,nj}/kT_E}$$

and hence, (IV.42),

$$r = \frac{4\pi}{c^2}\left(\frac{kT_E}{2\pi m}\right)^{3/2} \sum_{n=1}^{\infty} \frac{g_{nj}}{g_{cj}} \varkappa_{nj}\left[\left(\frac{hv_{o,nj}}{kT_E} + 1\right)^2 + 1\right] \qquad \text{(IV.46)}$$

Applications. The coefficient $\varkappa_{nj}(v)$ do not follow the same law as a function of the frequency. Whereas for hydrogen $\varkappa_{nj}(v)$ is always proportional to v^{-3}, the other atoms exhibit different behaviors according to their states. The normal state is never hydrogenlike, whereas the higher states rapidly become hydrogenlike.

Hydrogen

Relation (IV.43) is applicable where $g_{nj} = 2n^2$ (n = 1, 2) and $g_{cj} = 1$. Morevoer, since

$$\varkappa_{nj}(\nu) = C_{nj}\nu^{-3} = \frac{2^6\pi^4\varepsilon^{10}m}{3\sqrt{3}\,ch^6n^5}\;\nu^{-3}$$

we obtain (IV.43)

$$r = \frac{2^9\pi^5\varepsilon^{10}m}{c^3h^3}\left(\frac{1}{6\pi mkT_E}\right)^{3/2}\sum_{n=1}^{\infty} e^{\,h\nu_{o,nj}/kT_E}\frac{1}{n^3}\,\mathrm{E}i\left(\frac{h\nu_{o,nj}}{kT_E}\right)$$

For $T_E = 300°K$, we have summarized in the following table the values of

$$\sum_{n=1}^{x} e^{\,h\nu_{o,nj}/kT_E}\frac{1}{n^3}\,\mathrm{E}i\left(\frac{h\nu_{o,nj}}{kT_E}\right)$$

Table 3

x = 1	$1.897\cdot10^{-3}$	x = 5	$4.286\cdot10^{-3}$	x = 25	$6.589\cdot10^{-3}$
2	$2.840\cdot10^{-3}$	10	$5.400\cdot10^{-3}$	30	$6.766\cdot10^{-3}$
3	$3.463\cdot10^{-3}$	15	$5.978\cdot10^{-3}$	40	$6.998\cdot10^{-3}$
4	$3.926\cdot10^{-3}$	20	$6.343\cdot10^{-3}$	50	$7.141\cdot10^{-3}$

Hence, the recombination coefficient of hydrogen, with $T_E = 300°K$, is

$$r_H = 4.5\cdot10^{-12} \tag{IV.47}$$

Oxygen

For the initial state 2p, expression (IV.46) is used and

$$r(2p) = 0.56\cdot10^{-12}$$

For the higher states considered to be hydrogenlike, with $n = 4$ to 50,

$$\sum_{n=4}^{50} r_n = 2{,}32\times10^{-12}$$

Whence

$$r_0 = r(2p) + \sum_{n=4}^{50} r_n = 2.88 \times 10^{-12} \qquad (IV.48)$$

Nitrogen

For the initial state 2p, expression (IV.45) gives

$$r(2p) = 0.32 \cdot 10^{-12}$$

The higher states are also considered to be hydrogenlike and hence

$$r_N = r(2p) + \sum_{n=4}^{50} r_n = 2.64 \times 10^{-12} \qquad (IV.49)$$

Helium

For the S states, we must consider (IV.44), and we obtain

$$r(1^1S) = 0.985 \cdot 10^{-12} \qquad (IV.50)$$

$$r(2^3S) = 1 \cdot 10^{-13} \qquad (IV.51)$$

$$r(2^1S) = 2.96 \cdot 10^{-14} \qquad (IV.52)$$

For the P states, expression (IV.43) applies; whence

$$r(2^3P) = 1.01 \cdot 10^{-13} \qquad (IV.53)$$

$$r(2^1P) = 1.8 \cdot 10^{-14} \qquad (IV.54)$$

Considering the hydrogenlike atom for the higher states with $n = 3$ to 50

$$\sum_{n=3}^{50} r_n = 3.33 \times 10^{-12} \qquad (IV.55)$$

Finally, (IV.50 to 55),

$$r_{He} = 4.56 \cdot 10^{-12} \qquad (IV.56)$$

Molecules. Since it is impossible to determine the recombination in the various states in the case of molecules, we postulate a value of the recombination of the same order of magnitude as that of the atoms. Hence,

$$r_{O_2} = r_{N_2} = 2 \cdot 10^{-12} \qquad (IV.57)$$

Case 2. Attachment of electrons, coefficient a.

The radiative attachement process is the reverse of the photo-detachment process and thus corresponds to the mechanism of radiative recombination. Relation (IV.46) may be applied mutatis mutandis

$$a_j = \frac{4\pi}{c^2} \left(\frac{kT_E}{2\pi m}\right)^{3/2} z_j \frac{g_j}{g} \left[\left(\frac{h\nu_{o,j}}{kT_L} + 1\right)^2 + 1\right] \qquad (IV.58)$$

Application. Relation (IV.58) can only be applied if the exact value of the energy of detachment is known. In the absence of this value, one can assume with Massey (Negative Ions, Cambridge, 1938) a probability of the order of $5 \cdot 10^{-6}$ per kinetic collision between an electron and an atom. We then have for

$$O + \epsilon \longrightarrow O^- + h\nu,$$
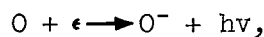
$$a = 2 \cdot 10^{-11} \cdot (1,840 \cdot 16)^{1/2} \cdot 5 \cdot 10^{-6} = 2 \cdot 10^{-14} \qquad (IV.59)$$

C. Disappearance of Negative and Positive Ions

Collisions between negative ions and positive ions, coefficient f.

A priori, the elementary mechanisms are the following:

(1) A double radiative collision between a negative ion A^- and a positive ion B^+ produces a molecular formation AB according to the equation

$$A^- + B^+ \longrightarrow AB + h\nu$$

(2) A triple collision between the ions and a third particle M which intervenes for the conservation of energy.

(3) A double collision causing a transformation of the ionization energy into excitation of the atoms

$$A^- + B^+ \longrightarrow A* + B* \text{ (excited atoms)}$$
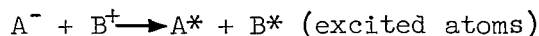
with
$$A* \longrightarrow A + h\nu$$

$$B* \longrightarrow B + h\nu$$

In the case of double collisions, it is necessary to determine the number of kinetic collisions of a negative ion A^- and a positive ion B^+ and to know the probability of molecular formation and of formation of neutral atoms. A formula analogous to (IV.36) results immediately. Hence, the most important mechanism will be that whose probability of formation of a molecule or of neutral atoms during the collision will be the greatest.

As far as triple collisions of charged particles are concerned, J. J. Thomson's formula (Ref. 74) permits an immediate application.

Applications. Among the various reactions in the upper atmosphere, we should retain that which involves an oxygen molecule

$$O^- + O_2^+ \longrightarrow O + O_2$$
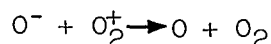
whose probability during a kinetic collision will be of the order of unity. It follows that this reaction alone should be retained to a first approximation, and we therefore obtain for the value of the coefficient f

$$f = 2 \cdot 10^{-11}. \tag{IV.60}$$

As far as reactions such as

$$O^- + O^+ \longrightarrow O + O$$

$$\text{(IV.61)}$$

$$O^- + N^+ \longrightarrow O + N$$
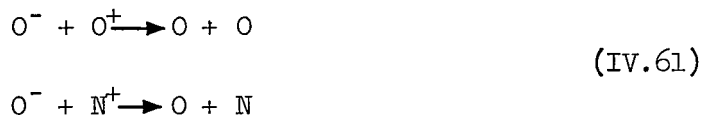
are concerned, a lower probability should be assumed. The excitation potential of $O(3^5P)$ is equal to 10.69 eV. This value is greater by 0.20 ± 0.08 eV than the difference between the ionization potential (13.56 eV) and the affinity (3.07 ± 0.08 eV) of OI. The difference, 11.42 ± 0.08 eV between the ionization potential of NI (14.49 eV) and the affinity of OI is lower than the excitation potential of the closest excited state, $3p^2S_{1/2}$, of NI. However, the agreement in resonance is better if one considers the reaction

$$O^- + N^+ \longrightarrow N(^2D) + O(3^5S) \qquad \text{(IV.62)}$$
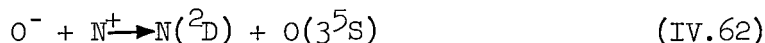
where the difference between the ionization potential and the affinity (11.42 ± 0.08 eV) does not differ very much from the sum of the excitation potentials of $N(^2D)$ and $O(3^5S)$: $2.37 + 9.11 = 11.48$ eV.

As far as the effect of the mechanism

$$O^- + N_2^+ \longrightarrow N_2(\text{excited}) + O(^1S) \qquad \text{(IV.63)}$$
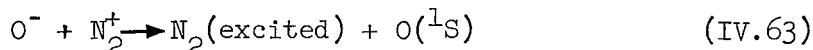
is concerned, it should be important in the production of the light of the night sky, but does not seem to immediately affect the ionization state.

CHAPTER V. PHYSICAL INTERPRETATION OF THE IONOSPHERE

Section 1. Introduction

The elements necessary for a physical interpretation of the iono-
sphere, which result both from data provided by observations (Chapter I)
and from results obtained on the solar emission (Chapter II) on the
structure and composition of the atmosphere (Chapter III) and on the
state of ionization (Chapter IV), are now known through the study which
we carried out in the preceding chapters. It will be remembered that
the characteristic results of systematic observation of the various
regions of the ionosphere should be interpreted by the ionization equi-
librium. This equilibrium is due to the photoionization by the solar
radiations and to the disappearance of electrons as a result of elemen-
tary mechanisms within the physical medium of the upper atmosphere
$(h > 90$ km). Consequently, we can proceed from this basis to a theo-
retical study of the ionosphere, which will lead to an interpretation
of the principal phenomena observed.

Section 2. Formation of an Ionized Region

The general ionization equations (III.1, 2 and 3), applied to a
given element of the upper atmosphere, may be written, by removing the
species index,

$$\frac{\partial N_E}{\partial t} = Ni + N^- d + pNN^- - aNN_E - rN^+ N_E \qquad (V.1)$$

$$\frac{\partial N^+}{\partial t} = Ni - fN^+ N^- - rN^+ N_E \qquad (V.2)$$

$$\frac{\partial N^-}{\partial t} = aNN_E - N^- d - pNN^- - fN^+ N^- \qquad (V.3)$$

Let us recall at this point the meaning of the various symbols used
(cf. Chapter IV, p. 94); N, N^+, N^- and N_E represent respectively the

concentrations of neutral atoms or molecules, positive ions, negative
ions and electrons; i is the ionization coefficient; d is the coeffi-
cient of photodetachment; a is the coefficient of radiative attachment;

p is the coefficient of detachment by collision; r and f are, respectively, the coefficients of spontaneous recombination of electrons and negative ions with positive ions.

Since the ionospheric medium is assumed to be electrically neutral, it is postulated that the number of positive charges is equal to the number of negative charges,

$$N^+ = N^- = N_E \qquad (V.4)$$

and equations (V.1, 2 and 3) are not independent, since, (V.4),

$$\frac{\partial N^+}{\partial t} = \frac{\partial N^-}{\partial t} + \frac{\partial N_E}{\partial t} \qquad (V.5)$$

In equations (V.1, 2 and 3), a part of the terms is due to the absorption of solar energy, while the other part is due to elementary mechanisms affecting the neutral and charged particles within the upper atmosphere. It is necessary to consider the distribution of the absorbed energy which causes the ionization of neutral atoms, and to determine the processes of recombination and attachement which are the cause of the disappearance of electrons. Hence, it is possible to investigate the conditions under which an ionized region can be formed, i.e., under what conditions a maximum of the electron concentration exists at a fixed altitude.

To this end, let us consider the stationary state where we have

$$\frac{\partial N^+}{\partial t} = \frac{\partial N^-}{\partial t} = \frac{\partial N_E}{\partial t} \equiv 0 \qquad (V.6)$$

Furthermore, let us set

$$u \equiv \frac{N^-}{N_E} > 0 \qquad (V.7)$$

whence, (V.4),

$$u + 1 \equiv \frac{N^+}{N_E} > 0 \qquad (V.7')$$

From (V.6, 7 and 7'), account being taken of (IV.22), the initial equations (V.1, 2 and 3) assume the form

$$Ni_{\infty} \, e^{-\dfrac{\varkappa h \mathrm{N}}{\sin h \odot}} + (d + p\mathrm{N})u\mathrm{N_E} = a\mathrm{N}\mathrm{N_E} + r(1 + u)\mathrm{N_E^2} \qquad (\mathrm{V.8})$$

$$Ni_{\infty} \, e^{-\dfrac{\varkappa h \mathrm{N}}{\sin h \odot}} = (r + uf)(1 + u)\mathrm{N_E^2} \qquad (\mathrm{V.9})$$

$$a\mathrm{N} = u \, [d + p\mathrm{N} + (1 + u)f\mathrm{N_E}] \qquad (\mathrm{V.10})$$

Equation (V.9) immediately gives the expression for $\mathrm{N_E}$

$$\mathrm{N_E} = \sqrt{\dfrac{Ni_{\infty} \, e^{-\dfrac{\varkappa h \mathrm{N}}{\sin h \odot}}}{(r + uf)(1 + u)}} \, . \qquad (\mathrm{V.11})$$

where the numerator corresponds to the electron production by photoionization and where the denominator represents the recombination coefficient

$$\alpha \equiv (r + uf)(1 + u) \qquad (\mathrm{V.12})$$

In order to determine the condition of formation of an ionized region, we have to express the condition of an electron concentration maximum at altitude z. Since the molecular concentration at altitude z is given by relation (III.38)

$$\mathrm{N} = \mathrm{N_0} \, e^{-z/h},$$

we can replace the independent variable z by N. Hence, we shall differentiate expression (V.8) with respect to N. We obtain, (V.8),

$$i_{\infty} \, e^{-\dfrac{\varkappa h \mathrm{N}}{\sin h \odot}} (1 - \dfrac{\varkappa h \mathrm{N}}{\sin h \odot}) + (d + p\mathrm{N} - r\mathrm{N_E})\mathrm{N_E} \dfrac{\partial u}{\partial \mathrm{N}} = (a - pu)\mathrm{N_E} \, .$$

Similarly, by differentiating equation (V.10) with respect to N, we obtain the expression

$$a - pu = [d + p\mathrm{N} + f(1 + 2u)\mathrm{N_E}] \dfrac{\partial u}{\partial \mathrm{N}}$$

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which, introduced into the preceding relation, yields

$$i_\infty e^{-\frac{\varkappa h N}{\sin h_\odot}} (1 - \frac{\varkappa h N}{\sin h_\odot}) = \frac{\partial u}{\partial N} [r + (1 + 2u)f] N_E^2 \tag{V.13}$$

Taking (V.9) into account, the latter equation is written as

$$\boxed{1 - \frac{\varkappa h N}{\sin h_\odot} = \frac{r + (1 + 2u)f}{(1 + u)(r + uf)} N \frac{\partial u}{\partial N}} \tag{V.14}$$

This is the general expression providing the condition of a maximum in the vertical distribution of the electron concentration, an expression which, incidentally, results immediately from (V.11) by cancellation of the derivative with respect to N.

Let us now determine under what conditions (V.14) is practically verified. To this end, we have to find the values of u which satisfy this equation. Equation (V.10) may be written in the form

$$u = \frac{aN}{pN + d + f(1 + u)N_E} \tag{V.15}$$

or

$$u = \frac{a}{p} \cdot \frac{1}{1 + \dfrac{d + f(1 + u)N_E}{pN}} \tag{V.15'}$$

and, by differentiating with respect to N,

$$\frac{\partial u}{\partial N} = \frac{a - pu}{pN + d + f(1 + 2u)N_E} \tag{V.16}$$

where we note immediately that the terms of the denominator involve the three coefficients d, p and f, corresponding to the various processes of disappearance of the negative ions.

Let us consider the possible cases, a priori, in order to deduce the practical conditions of formation of the ionized regions.

Case 1. Let us assume that in equation (V.16)

$$a - pu = 0 \qquad \text{(V.17)}$$

so that

$$\frac{\partial u}{\partial N} = 0 \qquad \text{(V.18)}$$

Condition (V.17) will be met in (V.15) when

$$pN > d + (1 + u)fN_E \qquad \text{(V.19)}$$

i.e., when the last two terms in the denominator of (V.15) can be neglected in the presence of pN.

Taking (V.18) into account in expression (V.14), from the condition of a maximum of the electron concentration, we immediately obtain the formula

$$1 - \frac{\varkappa hN}{\sinh_\odot} = 0 \qquad \text{(V.20)}$$

This last expression (V.20) defines the condition of the maximum of electron production by photoionization. Indeed, by cancelling the derivative with respect to N of (cf. IV.22 and V.9)

$$Ni = Ni_\infty \, e^{-\dfrac{\varkappa hN}{\sinh_\odot}} \qquad \text{(V.21)}$$

representing the electron production by photoionization, we obtain the condition (V.20) of the maximum.

Consequently, the formation of an ionized region is possible in the case (V.17 and 19) where the ratio u of negative ions to electrons is determined by the process of collision with neutral particles. Such an ionospheric region is characterized by a maximum electron concentration at the level of maximum production by photoionization. Furthermore, the effective recombination coefficient is given by, (V.12 and 17),

$$\alpha = \frac{1}{p^2} \, (a + p)(af + rp) \qquad \text{(V.22)}$$

Finally, from (V.20), we deduce for (V.11)

$$(N_E)_{max} = \sqrt{\frac{Ni}{\alpha}} = \sqrt{\frac{i_\infty}{\varkappa hc\alpha}} \, (\sin h_\odot)^{\frac{1}{2}} \qquad (V.23)$$

where the value of α is given by (V.22) and e is the base of natural logarithms.

Case 2. Assuming that relation (V.17) is realized, we obtain from the practical standpoint the largest value of u

$$u = \frac{a}{p}$$

since, (V.15'),

$$\frac{d + f(1 + u)N_E}{pN} > 0$$

If we assume that condition (V.17) is not realized, we must write

$$pu < a \qquad (V.24)$$

Then, (V.16),

$$\frac{\partial u}{\partial N} \simeq \frac{a}{d + pN + (1 + 2u)fN_E} \qquad (V.25)$$

since pu may be neglected in the presence of a.

Two subcases are possible:

(a)

$$d > pN + (1 + 2u)fN_E \qquad (V.26)$$

and hence, (V.25 and 15), the approximate relations

$$\frac{\partial u}{\partial N} \simeq \frac{a}{d} \qquad (V.27)$$

$$u \simeq \frac{aN}{d} \simeq N \frac{\partial u}{\partial N} \qquad (V.28)$$

Expression (V.14) is written to an acceptable approximation, (V.25), based on (V.27 and 28), as

$$\frac{\varkappa h N}{\sinh_\odot} \simeq \frac{r - u^2 f}{(1 + u)(r + uf)} \qquad (V.29)$$

Since the first member of (V.29) is always positive, one must have, in the case of a maximum of N_E,

$$r - u^2 f > 0$$

where $u^2 < \dfrac{r}{f} = 0.1$,

since, (IV.57 and 60), $r = 2 \cdot 10^{-12}$ and $f = 2 \cdot 10^{-11}$.

In this case, we immediately verify the fact that the effective recombination coefficient, (V. 12), is

$$\alpha = (1 + u)(r + uf) < 10^{-11} \qquad (V.30)$$

Moreover, if in expression (V.29) the terms uf and $u^2 f$ are negligible compared to r, we have

$$\alpha \simeq r = 2 \cdot 10^{-12} \qquad (V.31)$$

and

$$\frac{\varkappa h N}{\sinh_\odot} = 1 \qquad \qquad .$$

This last expression defines the condition (V.20) of the maximum for the electron production by photoionization.

Consequently, the formation of an ionized region is possible in the case (condition V.26) where photodetachment is the main process responsible for the disappearance of negative ions. The properties of such a region would be as follows:

(1) In a region (relation V.31) where the level of the maximum electron concentration corresponds to that of the production by photo-ionization, the ratio u of the concentrations of negative ions to

electrons is negligible in the expression (V.22) of the effective recombination coefficient. Hence, the coefficient of spontaneous recombination, $r = 2 \cdot 10^{-12}$, is the effective value of the coefficient, and (V.11) is written as

$$\dot{N}_E = \sqrt{\frac{\overline{Ni}}{r}}$$

and finally, (V.20 and 21),

$$(N_E)_{max} = \sqrt{\frac{i_\infty}{\varkappa her}} \; (\sinh_C)^{\frac{1}{2}} \tag{V.32}$$

$$(e = 2.718)$$

(2) In a region (relations V.29 and 30) where the level of the maximum electron concentration is at an altitude exceeding that of the production by photoionization, the ratio u cannot surpass a value equal to 0.1. Hence, the effective recombination coefficient will not be able to reach a value equal to 10^{-11}.

(b) Let $\qquad\qquad (1 + u)fN > d + pN \tag{V.33}$

so that we have, to an excellent approximation, (V.15),

$$u = \frac{aN}{(1 + u)fN_E} \tag{V.34}$$

and, (V.25),

$$N \frac{\partial u}{\partial N} = \frac{aN}{(1 + 2u)fN_E} = \frac{u(1 + u)}{1 + 2u} \tag{V.35}$$

Taking (V.34) into account in (V.14), we immediately have

$$1 - \frac{\varkappa hN}{\sinh_\odot} = \frac{[r + (1 + 2u)f] \, u}{(r + uf)(1 + 2u)} \tag{V.36}$$

or

$$\frac{\varkappa h N}{\sin h_\odot} = \frac{r(u+1)}{(1+2u)(r+uf)} \qquad (V.36')$$

or, in another form, on the basis of (V.12)

$$\frac{\varkappa h N}{\sin h_\odot} = \frac{r(u+1)^2}{a(1+2u)} \qquad (V.36'')$$

These formulas (V.36) give in various forms the expression for the condition of a maximum electron concentration in the case where condition (V.33) is realized. In this case, the altitude of the maximum electron concentration is situated appreciably above the maximum altitude of the electron production.

In order to obtain the expression of this maximum electron concentration, let us reconsider equation (V.13), where we replace $\frac{\delta u}{\delta N}$ and the term between parentheses in the first member by their respective values (V.34 and 36). After immediate simplifications, we obtain the relation

$$(N_E)_{max} = \frac{i_\infty\, e^{-\frac{\varkappa h N}{\sin h_\odot}}}{a} \times \frac{uf}{r+uf} \qquad (V.37)$$

Since $f = 2 \cdot 10^{-11}$ and $r = 2 \cdot 10^{-12}$, we then have, for a value of $u > 1$, the approximate relation

$$(N_E)_{max} \simeq \frac{i_\infty e^{-\frac{\varkappa h N}{\sin h_\odot}}}{a} \qquad (V.38)$$

which gives the value of the maximum electron concentration at an altitude greater than that of the production.

The theoretical laws of the formation of an ionized region being determined, let us now return to the experimental laws deduced from the observations exposed in Chapter I.

We have seen that the maximum electron concentration of the E and F_1 regions obeys the law, (I.1),

$$(N_E)_{max} \div (\sin h_\odot)^{\frac{1}{2}} \qquad (V.39)$$

and that the effective recombination coefficient is greater than 10^{-8}. In the F_2 region, the law (V.39) does not apply, and the recombination

coefficient is generally comprised between 10^{-10} and 10^{-11}.

A comparison of these experimental results with the above theoretical results thus makes it possible to determine which among the cases studied apply to the various regions. Relations (V.20, 22 and 23), which define an ionized region where the maximum electron concentration is situated at the level of the maximum electron production by photoionization, should be applied to the E and F_1 regions. As far as the F_2 region is concerned, the only possibility of interpretation is provided by the case 2b studied (relations V.34 to 38) where the maximum electron concentration is situated at an altitude greater than that of the production maximum.

Section 3. Origin of the Ionospheric Regions

The search for the origin of the various ionized regions poses both the problem of absorption of solar energy and of its vertical distribution, related to the composition of the upper atmosphere. In Figure 15, we have collected the various data concerning solar emission (determination made in Chapter II, Table 1, and Figure 11), and the absorption coefficients (calculations of Chapter IV, Case 1) of the various atmospheric constituents (studies made in Chapter III). We immediately find that the ionization of atomic oxygen (O), atomic nitrogen (N) and molecular nitrogen (N_2) and helium (He) results from the radiation of $\lambda <$ 910 $\overset{o}{A}$, corresponding to the ionization potential of hydrogen. Hence, on the basis of the conclusions of Chapter II, we must assume that ionization of these constituents is due to the emission of chromospheric radiation. Molecular oxygen (O_2) and the compounds NO and NO^+ are subjected to the radiation of $\lambda >$ 910 $\overset{o}{A}$. On the other hand, we have shown in Chapter III that O_2 and NO characterize solely the region of the E layer, whereas the other constituents O, N, N_2 and He are present in the whole upper atmosphere. Hence, the chromospheric radiative energy of $\lambda <$ 910 $\overset{o}{A}$

EMISSION AND ABSORPTION OF SOLAR RADIATION

Number of quanta (per sec per cm²) usable at top of atmosphere

Eruptions

$L_\alpha \left\{ \begin{array}{l} 7 \times 10^9 \\ \text{à} \\ 9.7 \times 10^{12} \end{array} \right.$

L_α | | | 2.7 × 10⁶ | 2.2 × 10⁷ He λ 584 | 1.3 × 10⁵ Chromosphere
| < 8 × 10¹³ | | | < 10³ | Minimum radiation

6000°	1.2 × 10¹⁷	2.2 × 10¹⁴	1.1 × 10¹²	a d g	2.2 × 10⁷	3.0 × 10⁴	1.4	Continuous
5740°	9.2 × 10¹⁶	3.7 × 10¹³ 4.3 × 10¹¹	b e h	5.9 × 10⁶	1.4 × 10⁴	0.18	spectrum
5000°	3.5 × 10¹² 2.2 × 10¹⁰	c f j	4.65 × 10⁴	3.3	9.5 × 10⁻³	

O_2 NO O_2 O N N_2, O_2 N_2 He

Absorption coefficients

a = 7 × 10⁹
b = 1.8 × 10⁹
c = 4.8 × 10⁷
d = 2.9 × 10⁶
e = 2.5 × 10⁶
f = 3.6 × 10⁶
g = 1.3 × 10⁶
h = 3.8 × 10⁷
j = 4.1 × 10⁵

Figure 15

will be absorbed by these latter elements. The absorption caused by O, N (see below) is total at an altitude greater than that of the E region, so that the O_2 molecule cannot be subjected to photoionization via absorption in the continuum at $\lambda < 765$ Å. Thus, two absorption regions in the upper atmosphere correspond to the two regions of solar emission at $\lambda <$ or > 910 Å.

In the preceding section, we have shown that if only one element is considered, the E and F_1 regions were defined, among others, by relation (V.20)

$$\frac{\varkappa hN}{\sinh_{\odot}} = 1 \quad \text{or} \quad \varkappa hN_M = 1, \quad (h_{\odot} = 90°) \qquad (V.40)$$

where $\varkappa$ is an average value of the absorption coefficient, h is the ration of logarithmic decrease of the molecular concentration, and N or N_M is the molecular concentration at the level of maximum absorption, depending on whether $h_{\odot}$ is smaller than or equal to $90°$.

The F Regions

For the upper regions of the ionosphere, observation (Appleton, Ref. 74; Pekeris, Ref. 75) gives values from 30 to 40 km for an ionospheric height scale which we compare to the rate of logarithmic decrease h of the molecular concentration. Moreover, if we consider the average values of the absorption coefficients (see Figure 15) of O, N, N_2 and He, we obtain the following results by applying formula (V.40).

For oxygen, if $\varkappa = 1.45 \cdot 10^{-17}$, we write

$$N_M(O) \cdot 1.45 \cdot 10^{-17} \cdot 3 \cdot 10^6 = 1$$

or

$$N_M(O) \cdot 1.45 \cdot 10^{-17} \cdot 4 \cdot 10^6 = 1$$

whence

$$N_M(O) = 1.7 \text{ to } 2.3 \cdot 10^{10} \qquad (V.40a)$$

Similarly, for atomic nitrogen, when $\varkappa = 1.75 \cdot 10^{-17}$, we have

$$N_M(N) = 1.4 \text{ to } 1.9 \cdot 10^{10} \qquad (V.40b)$$

In the same manner, for molecular nitrogen when $\varkappa = 10^{-17}$, we find

$$N_M(N_2) = 3.3 \cdot 2.5 \cdot 10^{10} \qquad (V.40c)$$

and if $\varkappa = 10^{-18}$

$$N_M(N_2) = 3.3 \cdot 2.5 \cdot 10^{11} \qquad (V.40d)$$

Finally, for helium, when $x = 8 \cdot 10^{-18}$, we obtain

$$N_M(\text{He}) = 3.1 \text{ to } 5 \cdot 10^{10} \qquad (\text{V.40f})$$

These relations (V.40a to f) determine the numbers of atoms or molecules (per cm^3) at the level of maximum photoionization in the case where only one element subjected to ionization is considered. We see, however, that the atomic or molecular concentration is of the order of 10^{10}; hence, we find that we are dealing with an atmospheric region corresponding to the F region, and thus, the ionization of the F region results from the solar chromospheric emission of wavelengths smaller than 910 Å.

We now have to determine which atoms or molecules are susceptible of forming this F_1 region. Let us, therefore, consider the various spectral regions (see Figure 15) which pertain to these various constituents and write the expressions for the absorption of radiation of $\lambda < 910$ Å.

$$N_0(\text{He}) e^{-z/h} \, i_{5\infty} e^{-[\bar{\varkappa}_5(O) N_0(O) + \bar{\varkappa}_4(N) N_0(N) + \bar{\varkappa}_1(\text{He}) N_0(\text{He})] h \, c^{-z/h}} \qquad (\text{V.41})$$

$$N_0(N_2) e^{-z/h} \, i_{4\infty} e^{-[\bar{\varkappa}_4(O) N_0(O) + \bar{\varkappa}_3(N) N_0(N) + \bar{\varkappa}_2(N_2) N_0(N_2)] h \, c^{-z/h}} \qquad (\text{V.42})$$

$$N_0(N_2) e^{-z/h} \, i_{3\infty} e^{-[\bar{\varkappa}_3(O) N_0(O) + \bar{\varkappa}_2(N) N_0(N) + \bar{\varkappa}_1(N_2) N_0(N_2)] h \, c^{-z/h}} \qquad (\text{V.43})$$

$$N_0(N) e^{-z/h} \, i_{2\infty} e^{-[\bar{\varkappa}_2(O) N_0(O) + \bar{\varkappa}_1(N) N_0(N)] h \, e^{-z/h}} \qquad (\text{V.44})$$

$$N_0(O) e^{-z/h} \left\{ i_{1\infty} e^{-[\bar{\varkappa}_1(O) h N_0(O) e^{-z/h}} \quad + i_{2\infty} e^{-[\bar{\varkappa}_2(O) h N_0(O)} \right.$$
$$\left. + \bar{\varkappa}_1(N) h N_0](N) \, e^{-z/h} \right\} \qquad (\text{V.45})$$

where (see Figure 15)

$$\begin{cases} \bar{\varkappa}_1(O) = 1.35 \times 10^{-17}, \ i_{1\infty}(O) = \bar{\varkappa}Q = 1.36 \times 10^{-8}; \ Q = 1.01 \times 10^{9} \\ \bar{\varkappa}_2(O) = 1.4 \ \times 10^{-17}, \ i_{2\infty}(O) = 7.28 \times 10^{-9}; \ Q = 5.2 \times 10^{8} \end{cases} \quad (V.46)$$

$$\begin{cases} \bar{\varkappa}_1(N) = 2.05 \times 10^{-17}, \ i_{2\infty}(N) = 1.07 \times 10^{-8} \end{cases} \quad (V.47)$$

$$\begin{cases} \bar{\varkappa}_3(O) = 1.5 \ \times 10^{-17} \\ \bar{\varkappa}_2(N) = 1.85 \times 10^{-17} \\ \bar{\varkappa}_1(N_2) = 10^{-18} \end{cases} 1.7 \times 10^{-17} \begin{array}{l} , \ i_{3\infty}(O) = 3.75 \times 10^{-9}; \ Q = 2.5 \times 10^{8} \\ , \ i_{3\infty}(N) = 4.62 \times 10^{-9} \\ , \ i_{3\infty}(N_2) = 2.5 \ \times 10^{-10} \end{array} \quad (V.48)$$

$$\begin{cases} \bar{\varkappa}_4(O) = 1.475 \times 10^{-17} \\ \bar{\varkappa}_3(N) = 1.5 \ \times 10^{-17} \\ \bar{\varkappa}_2(N_2) = 10^{-17} \end{cases} 1.49 \times 10^{-17} \begin{array}{l} , \ i_{4\infty}(O) = 3.25 \times 10^{-10}; \ Q = 2.2 \times 10^{7} \\ , \ i_{4\infty}(N) = 3.3 \ \times 10^{-10} \\ , \ i_{4\infty}(N_2) = 2.2 \ \times 10^{-10} \end{array} \quad (V.49)$$

$$\begin{cases} \bar{\varkappa}_5(O) = 1.25 \times 10^{-17} \\ \bar{\varkappa}_4(N) = 1.20 \times 10^{-17} \\ \bar{\varkappa}_1(He) = 0.75 \times 10^{-17} \end{cases} 1.225 \times 10^{-17} \begin{array}{l} , \ i_{5\infty}(O) = 1.625 \times 10^{-12}; \ Q = 1.3 \times 10^{5} \\ , \ i_{5\infty}(N) = 1.56 \ \times 10^{-12} \\ , \ i_{5\infty}(He) = 9.75 \ \times 10^{-13} \end{array} \quad (V.50)$$

By cancelling the derivatives of expression (V.41 to 45), we obtain the conditions for the photoionization maxima.

For He, we find, (V.41),

$$\bar{\varkappa}_5(O) h N_0(O) + \bar{\varkappa}_4(N) h N_0(N) + \bar{\varkappa}_1(He) h N_0(He) = c^{z/h}$$

Since

$$\frac{i_{1\infty}(O)}{i_{5\infty}(He)} = 1.5 \cdot 10^{4}$$

and

$$\frac{\bar{\varkappa}_5 h N_0(O) + \bar{\varkappa}_4 h N_0(N)}{\bar{\varkappa}_1 h N(He)} = 1.6 \ \frac{N(O) + N(N)}{N(He)}$$

Since it is certain that

$$N(He) < 1.5 \times 10^{4} [N(O) + N(N)]$$

we practically have, at the level of maximum photoionization of He,

$$\overline{\varkappa}_5(O)hN(O) + \overline{\varkappa}_4(N)hN(N) = 1 \qquad (V.51)$$

In other words, the altitude of the maximum electron production of helium is conditioned by the altitude of atomic oxygen and nitrogen.

For N_2 and $\overline{\varkappa}_2(N_2) = 10^{-17}$, we have the condition, (V.42),

$$\overline{\varkappa}_4(O)h\,N_0(O) + \overline{\varkappa}_3(N)h\,N_0(N) + \overline{\varkappa}_2(N_2)h\,N_0(N_2) = c^{z/h}$$

Since

$$\frac{i_{1\infty}(O)}{i_{4\infty}(N_2)} = \frac{1.36 \times 10^{-8}}{2.2 \times 10^{-10}} = 62$$

and

$$\frac{\overline{\varkappa}_4(O)h N_0(O) + \overline{\varkappa}_3(N)h N_0(N)}{\varkappa_2 h N_0(N_2)} = 1.49 \frac{N(O) + N(N)}{N(N_2)}$$

Since, in the atmosphere,

$$N(N_2) < 62\,[N(O) + N(N)]$$

we practically obtain

$$\overline{\varkappa}_4(O)h\,N(O) + \overline{\varkappa}_3(N)h\,N(N) = 1 \qquad (V.52)$$

With $\overline{\varkappa}_1(N_2) = 10^{-18}$, we have the condition (V.43),

$$\overline{\varkappa}_3(O)h\,N_0(O) + \overline{\varkappa}_2(N)h\,N_0(N) + \overline{\varkappa}_1(N_2)h\,N_0(N_2) = c^{z/h}$$

Since

$$\frac{i_{1\infty}(O)}{i_{3\infty}(N_2)} = \frac{1.36 \times 10^{-8}}{2.5 \times 10^{-10}} = 54$$

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and

$$\frac{\bar{\varkappa}_3(O)hN_0(O) + \bar{\varkappa}_2(N)hN_0(N)}{\bar{\varkappa}_1 hN_0(N_2)} = 17 \ \frac{N(O) + N(N)}{N(N_2)}$$

Hence, we have, to the best approximation,

$$\bar{\varkappa}_3(O)h\,N(O) + \bar{\varkappa}_2(N)h\,N(N) = 1 \qquad\qquad (V.53)$$

By virtue of relations (V.52 and 53), the maximum electron produc-
tion of molecular nitrogen is determined by the abundance of oxygen and
of atomic nitrogen.

Let us note, however, that if the effective number Q of quanta
reaching the top of the atmosphere were fixed by the helium line (λ

584 Å), the ionization of N_2 would be stronger. However, we can imme-

diately realize, on the basis of an observational fact, that relation

(V.52) will always apply whether the number of λ 584 Å quanta does not
exceed the normal chromospheric emission or whether the number of N_2

molecules is very low. Indeed, since the F region exists even in winter
in the polar regions (Tromsö, for example) when the sun does not illumi-
nate the lower atmosphere (h $<$ 35 km), the atmospheric element which
effectively produces this region must still be subjected to an ionizing
radiation which does not pass through the lower atmosphere. Since mole-
cular nitrogen is a constituent of the middle and lower atmosphere,
the radiations which should ionize it at the altitude of the F region
are absorbed before reaching it. Only the atoms of oxygen and nitrogen,
the constitutive elements of the upper atmosphere, can be ionized at all

times by radiations ($> \lambda$ 584 Å) exceeding those susceptible of ionizing
molecular nitrogen. For N, we obtain, (V.44), for the maximum condition

$$\bar{\varkappa}_2(O)hN_0(O) + \bar{\varkappa}_1(N)hN_0(N) = e^{z/h} \qquad\qquad (V.54)$$

or

$$\bar{\varkappa}_2(O)hN(O) + \bar{\varkappa}_1(N)hN(N) = 1 \qquad\qquad (V.55)$$

if we consider the corresponding altitude as the initial level. The
condition for the maximum photoionization of atomic nitrogen depends,

therefore, on that of atomic oxygen if the abundance of the latter is not negligible.

For O, we have, (V.45), as the condition of the maximum, the expression

$$i_{1\infty}(O)e^{-\bar{\varkappa}_1(O)hN_0(O)\,e^{-z/h}}\left[1 - \bar{\varkappa}_1(O)hN_0(O)\,e^{-z/h}\right] + \qquad (V.56)$$

$$i_{2\infty}(O)e^{-[\bar{\varkappa}_2(O)hN_0(O) + \bar{\varkappa}_1(N)hN_0(N)]e^{-z/h}}\left\{1 - [\bar{\varkappa}_2(O)hN_0(O) + \bar{\varkappa}_1(N)hN_0(N)]e^{-z/h}\right\} = 0$$

Let us note that

$$i_{1\infty}(O) = 1.868\ i_{2\infty}(O)$$

$$\bar{\varkappa}_1(O) = 1.35 \cdot 10^{-17} \simeq \bar{\varkappa}_2(O) = 1.4 \cdot 10^{-17}$$

and let us set

$$\zeta \equiv \bar{\varkappa}_1(O)hN_0(O) < 1$$

$$y \equiv e^{-z/h} > 0$$

Finally, let us consider as the starting level the altitude of the photoionization maximum of N by adopting relation (V.55).

Hence, (V.56) is written in the form

$$\frac{1 - \zeta y}{y - 1}\,e^{\,y(1 - \zeta)} = 0.535.$$

In order to calculate this last expression, we have considered different values of ζ (or values of the abundance of O relative to N) to obtain the values given by the following table.

ς	$N(O)$	y	ςy	$N_{max}(O)$	$-z$
0.9	$13.1 \cdot N(N)$	1.06	0.954	$2 \cdot 10^{10}$	2 to 3.5 km
0.5	1.46	1.68	0.84	$1.78 \cdot 10^{10}$	15 to 20 km
0.4	0.97	2.1	0.84	$1.78 \cdot 10^{10}$	21 to 30 km
0.3	0.67	2.9	0.87	$1.84 \cdot 10^{10}$	31 to 42 km
0.2	0.365	4.8	0.96	$2 \cdot 10^{10}$	47 to 63 km
0.1	0.16	10	1	$2.1 \cdot 10^{10}$	69 to 92 km
0.05	0.09	20	1	$2.1 \cdot 10^{10}$	120 km

Let us collect the numerical results obtained by expressions (V.51, 52, 53, 54 and 56) where h = 40 to 30 km;

$$\text{He,} \quad N(O) + N(N) = 2.04 \cdot 10^{10} \text{ to } 2.72 \cdot 10^{10}$$

$$N_2(\varkappa = 10^{-17}), \quad N(O) + N(N) = 1.68 \cdot 10^{10} \text{ to } 2.24 \cdot 10^{10}$$

$$N_2(\varkappa = 10^{-18}), \quad N(O) + N(N) = 1.47 \cdot 10^{10} \text{ to } 1.96 \cdot 10^{10}$$

$$\text{N,} \quad N(O) + 1.46\, N(N) = 1.79 \cdot 10^{10} \text{ to } 2.38 \cdot 10^{10}$$

$$\text{O,} \quad N(O) = 1.78 \text{ to } 2.1 \cdot 10^{10}$$

We immediately recognize that all the values are of the same order of magnitude and thus, that the photoionization maximum is located at a level defined by the concentration $N(O) + 1.46\, N(N)$. However, if $N(O)$ was appreciably greater than $N(N)$ (for example, the first line of the table), the F_1 region would be formed almost exclusively by atomic oxygen. On the contrary, if the abundance of O were much lower than that of N, there would be tendency toward the formation of another region much lower than the F_1 region. In the extreme case (last line of the table) the photoionization maximum of O would take place at the altitude of the E region (120 km). But since the concentration would only be $2 \cdot 10^{10}$ oxygen atoms per cm^3 at 120 km, this possibility cannot be accepted.

In the final analysis, the origin of the F region results from the ionization of the oxygen and nitrogen atoms acted upon by chromospheric radiation with wavelengths of less than 910 Å. The other constituents, such as molecular nitrogen and helium, have their photoionization maxima at the same altitude as oxygen and atomic nitrogen. Moreover, the O_2 molecule, whose concentration is insignificant at this altitude, also has a photoionization maximum due to the absorption of $\lambda < 735$ Å in its continuum.[1] Hence, no radiation with $\lambda < 910$ Å can reach the E region.[1]

The E Region

Molecular oxygen has an absorption continuum which corresponds to its first ionization potential, $\lambda < 1,010$ Å, and whose coefficient is very low, $\varkappa = 10^{-21}$. However, in the spectral range (cf. Chapter IV, p. 102), the preionization bands of O_2 possess a more appreciable absorption coefficient, $4 \cdot 10^{-17}$. We thus see that the E region, which as we have seen is located in the transition region, $O_2 \longrightarrow O + O$, may be due to the ionization of the O_2 molecule, if the rate of logarithmic decrease h of O_2 corresponds to the "ionospheric height scale" observed.

We thus have to find the value of h; it can be determined as follows.

We have shown earlier, (III.76), that

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[1] By virtue of the relation $e^{1-\zeta-e^{-\zeta}}$ (formula 4.10 of the Introduction), the radiation with $\lambda < 910$ Å reaching the altitude of the E region ($\sim$100 to 120 km) is $< 10^{-7}$ of the radiation reaching the average altitude (240 km) of the F_1 region. Thus, the formation of the E region by O_2, subjected to the influence of radiation with $\lambda < 735$ Å, cannot be admitted.

$$z_{\max}(O) = z_{\max}(O_2 \rightarrow O + O) + h \log_e \frac{H}{H - h} \qquad (V.57)$$

i.e., that the altitude of the maximum concentration of the oxygen atom, $z_{\max}(O) = 105$ to 110 km, is related to the altitude of maximum dissociation of O_2 by relation (V.57) where h is the rate of logarithmic decrease of O_2 with the altitude, and H is the height of the homogeneous atmosphere at these altitudes.

By virtue of relation (V.20) applied to the dissociation and ionization, we have

$$\frac{N_D(O_2) \, \overline{\varkappa}_D}{N_I(O_2) \, \overline{\varkappa}_I} = 1 \qquad (V.58)$$

where the indices D and I pertain respectively to the dissociation and ionization. Since $\overline{\varkappa}_D = 8.02 \cdot 10^{-18}$ and $\overline{\varkappa}_I = 10^{-17}$, we obtain, (V.58),

$$\frac{N_D(O_2)}{N_I(O_2)} = 5 = e^{\Delta z/h} \qquad (V.59)$$

Consequently, the ratio of the numbers of O_2 molecules per cm^3 at the levels of maximum dissociation and ionization, respectively, is equal to 5 and corresponds to the distribution of O_2 in an atmosphere

where h characterizes its rate of decrease with altitude; Δz is the difference in altitude between the two levels considered and, by virtue of (V.59), this difference is given by

$$\Delta z = 1.61 \, h \qquad (V.60)$$

Let 107.5 ± 2.5 km be the value of $z_{\max}(O)$; by virtue of (V.57 and 60), we can then write

$$1.61 \, h = h \log_e \frac{H}{H - h} + 1.25 \cdot 10^6 \qquad (V.61)$$

if the altitude of the ionization maximum of the E region is 120 km (average altitude at our latitudes).

On the other hand, the results of ionospheric observations show that $h \leqslant 11$ km and $10 \leqslant H \leqslant 30$ km. Let us set successively $H = 10$ h, 5 h, 3 h and 2 h. From (V.61), we obtain

h = 8.3 km	h = 9 km	h = 10.4 km	h = 13.3 km
H = 83 km	H = 45 km	H = 31.2 km	H = 26.6 km

Hence, the only acceptable solution is

$$H \simeq 3 \, h$$

Taking into consideration the fact that $z_{max}(0)$ is defined only within ± 2.5 km,

$$h \simeq 10 \text{ km} \qquad (8 \text{ to } 10 \text{ km})$$

$$H \simeq 30 \text{ km} \qquad (22 \text{ to } 30 \text{ km})$$

Finally, let us note that if we assume the same vertical distribution for the oxygen atom as for the other constituents, relation (III.65) gives values of H from 20 to 30 km (recombination via double or triple collisions) when it is assumed that $h(O_2) = 10$ km.

Let us apply relation (V.40) to O_2; since $x = 4 \cdot 10^{-17}$, we have

$$N_M(O_2) \cdot 4 \cdot 10^{-17} \cdot 10^6 = 1$$

whence

$$N_M(O_2) \simeq 2.5 \cdot 10^{10} \tag{V.62}$$

and we thus arrive at the important result that the ionospheric height scale determined by ionospheric measurements (~ 10 km) corresponds in fact to the rate of decrease, h, of the O_2 molecule at the level of the

E region and not to the height, H, of the homogeneous atmosphere at these altitudes. The approximate value of H (~ 22 to 30 km) indicates that between the E and F regions the atmosphere does not undergo any abrupt variation in its structure. In other words, the upper atmosphere behaves as a continuous body from the standpoint of composition and temperature. Moreover, the difference in the ionospheric height scales (or the abrupt variation in the structure of the atmosphere) takes place in the atmospheric region characterized by the start of dissociation of O_2, i.e., in the zone separating the middle atmosphere ($H \sim 8$ km) from

the upper atmosphere ($H \sim 20$ to 40 km).

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Whereas the E region is due to the absorption of solar energy by preionization bands, the ionization resulting from the continuum of O_2 can insure the existence of an ionospheric region (by virtue of V.29) only in the atmospheric region where $N(O_2) > 10^{15}$, i.e., at the start of the D region.[1]

Consequently, the origin of the E region is due to the emission of photospheric radiation comprised between λ 1000 Å and λ 910 Å which ionizes (preionization) the oxygen molecule, whose rate of logarithmic decrease with altitude is identical to the ionospheric height scale.

Finally, the NO molecule, whose existence has been demonstrated (in Chapter III) in the atmospheric region located above the E region, is susceptible of being ionized by radiation with $\lambda < 1,350$ Å. In this spectral range (cf. Figure 15) the line L_α ($\lambda = 1,215.7$ Å) of hydrogen appears which may emit a number of quanta greater than that of the photosphere. Consequently, the essential phenomenon below the E region results from the ionization of NO.[1]

Section 4. Nocturnal Conditions

The conditions of formation of an ionized region being fixed (Section 2) and the vertical distribution of the ionized elements being known (Section 3), we now must find the laws governing the variation of the electron concentration with time and altitude. We shall consider a priori two cases corresponding, respectively, to the diurnal conditions (presence of solar radiation) and nocturnal conditions (absence of solar radiations). The latter case is simpler, because when the solar radiations no longer affect the ionosphere, equations (V.1, 2 and 3) become immediately simplified and we have

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[1]Inasmuch as O_2 and NO are involved in the ionization above the E region, it is not impossible that we might be dealing with a double D layer, one part of which is particularly sensitive during the fade-out (ionization of NO, see below). Finally, it would be desirable to elucidate the ionization of atmospheric sodium.

$$i = d \equiv 0 \tag{V.63}$$

i.e., the photoionization and photodetachment no longer affect the electron concentration. Under these conditions, it is possible to determine the laws of variation of electron concentration by considering only the most abundant molecules and atoms present in the E and F regions. Consequently, the reasoning applied to the main constituent susceptible of being ionized and of capturing an electron will be valid without any extensive modification in the case of a system with several constituents. If we assume that this element is the oxygen atom, equations (V.1, 2, 3) can be written, on the basis of (V.63), as

$$\frac{\partial N_E}{\partial t} = - aNN_E + pNN^- - rN^+N_E \tag{V.64}$$

$$\frac{\partial N^+}{\partial t} = - rN^+N_E - fN^+N^- \tag{V.65}$$

$$\frac{\partial N^-}{\partial t} = aNN_E - pNN^- - fN^+N^- \tag{V.66}$$

Let us recall that N_2, N^- and N^+ are functions of altitude z and time t, whereas N depends only on z.

On the basis of (V.4 and 7), equations (V.64, 65, 66) assume the form

$$\frac{\partial N_E}{\partial t} = - (a - pu) NN_E - r(1 + u)N_E^2 \tag{V.67}$$

$$(1 + u) \frac{\partial N_E}{\partial t} = - (r + uf)(1 + u)N_E^2 - N_E \frac{\partial u}{\partial t} \tag{V.68}$$

$$u \frac{\partial N_E}{\partial t} = (a - pu)NN_E - fu(1 + u)N_E^2 - N_E \frac{\partial u}{\partial t} \tag{V.69}$$

From (V.68 or 69) and (V.67), we obtain

$$u = \frac{aN - \dfrac{1}{1 + u} \dfrac{\partial u}{\partial t}}{pN + (f - r)N_E} \tag{V.70}$$

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The stationary value u_S of u is therefore given by, (V.70), $(N_E)_S$ denoting the corresponding value of N_E

$$u_S = \frac{aN}{pN + [f - r](N_E)_S} = \frac{a}{p\left[1 + \frac{f - r}{p} \frac{(N_E)_S}{N}\right]} \qquad (V.71)$$

and the greatest value, u_M, by

$$u_M = \frac{a}{p} \qquad (V.72)$$

account being taken of the fact that $f > r$.

If the state is not stationary, the value of u is a solution of equation (V.70), i.e., of the differential equation of first order and first degree of Riccati

$$\frac{\partial u}{\partial t} + (u + 1)\left\{ u[pN + (f - r)N_E] - aN \right\} = 0 \qquad (V.73)$$

or, in another form,

$$\frac{\partial u}{\partial t} + u^2[pN + (f - r)N_E] + u[pN + (f - r)N_E - aN] - aN = 0$$

This equation admits of the particular solution, $u_1 = -1$, and is, therefore, integrable by a quadrature. In fact, by setting

$$u = \frac{1}{\gamma} - 1 \qquad (V.75)$$

we find the linear differential equation

$$\frac{\partial \gamma}{\partial t} + [(a + p)N + (f - r)N_E]\, y = pN + (f - r)N_E \qquad (V.76)$$

whose general integral is written between the limits t_x and t, as follows:

$$y = e^{\displaystyle -\int_{t_x}^{t}[(a+p)N + (f-r)N_E]\,dt} \Bigg\{ y_x$$
$$+ \int_{t_x}^{t}[pN + (f-r)N_E]\,e^{\displaystyle \int_{t_x}^{t}[(a+p)N+(f-r)N_E]\,dt}\,dt \Bigg\} \qquad (V.77)$$

y_x being the value of y at time $t = t_x$.

Let us transform the expression between brackets, and we write (V.77), after having set

$$(a+p)N + (f-r)N_E \equiv \varphi\,(z,\,t) \equiv \varphi > 0$$

to simplify the notation, in the following manner

$$y = e^{\displaystyle -\int_{t_x}^{t}\varphi\,dt}\left[\, y_x - 1 + e^{\displaystyle \int_{t_x}^{t}\varphi\,dt} - aN \int_{t_x}^{t} e^{\displaystyle \int_{t_x}^{t}\varphi\,dt}\,dt \right] \qquad (V.78)$$

By considering an average value $\overline{N}_E$ of N_E in the time interval $t - t_x > 0$, we obtain, by application of the mean value theorem

$$y = y_r\, e^{\displaystyle -\overline{\varphi}(t-t_x)} + \frac{pN + (f-r)\overline{N}_E}{(a+p)N(f-r)\overline{N}_E}\left[1 - e^{\displaystyle -\overline{\varphi}(t-t_x)}\right] \qquad (V.79)$$

By setting $u = u_x$ at time t_x, we obtain, by means of (V.65),

$$\frac{1}{1 + u_x} = y_x$$

and, on the basis of (V.79), the following value of u

$$u = \left| \dfrac{\dfrac{aN(u_x + 1)}{aN - [pN + (f - r)\overline{N}_E]\,u_x}\,e^{\overline{\varphi}(t - t_x)} - 1}{\dfrac{[pN + (f - r)N_E](u_x + 1)}{aN - [pN + (f - r)\overline{N}_E]u_x}\,e^{\overline{\varphi}(t - t_x)} + 1} \right| \tag{V.80}$$

with $\phi = (a + p)N + (f - r)\overline{N}_E$.

This expression thus provides a solution of equation (V.70), where $\overline{N}_E$ is an average value of N_E in the interval $t - t_x$.

Let us set

$$N_E = \overline{N}_E + \triangle N_E \tag{V.81}$$

where $\triangle N_E$ represents, in the interval $t - t_x$, the fluctuation of N_E with respect to an average value in this interval. In the ionosphere, we can chose a time interval such that $\triangle N_E$ is negligible in the pres-

ence of N_E. Hence, we can write to a sufficient approximation $N_E = \overline{N}_E$ amd take it into account in equation (V.80). We thus obtain an approximate value of u. Replacing u in equation (V.67) by its value given by (V.80), where N_E is considered instead of $\overline{N}_E$, we write the law governing

the local variation of the electron concentration as a function of time in the interval $t - t_x$ in the following form, which is directly appli-

cable to the ionospheric conditions:

$$\frac{\partial N_E}{\partial t} = \frac{(u_x + 1)\,e^{\varphi(t - t_x)}\left[(af + rp)N + r(f - r)N_E\right]N_E^2}{[pN + (f - r)N_E][u_x + 1]\,e^{\varphi(t - t_x)} - u_x] + aN}$$
$$+ \frac{(a + p)[aN - u_x pN - u_x(f - r)N_E]NN_E}{[pN + (f - r)N_E][(u_x + 1)\,e^{\varphi(t - t_x)} - u_x] + aN} \tag{V.82}$$

An examination of the relative values of the different times of equation (V.82) enables us to determine the simple laws which apply to the various regions of the ionosphere.

Case 1. Let us consider the condition

$$(u_x + 1)\, e^{\,\varphi(t - t_x)} - u_x < \frac{a\mathrm{N}}{p\mathrm{N} + (f - r)\mathrm{N_E}} \qquad (\mathrm{V}.83)$$

which, for a fixed value of N, i.e., at a certain altitude, can be set if the time interval $t - t_x$ is conveniently chosen. In fact, using the numerical data, we can verify the fact that in the observable regions of the ionosphere

$$\frac{a\mathrm{N}}{p\mathrm{N} + (f - r)\mathrm{N_E}} > 1 \qquad (\mathrm{V}.84)$$

Taking into account the condition (V.83), equation (V.82) is written, after a few elementary transformations, as

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (\mathrm{V}.85)$$
$$\frac{\partial \mathrm{N_E}}{\partial t} = -\left\{a + p\left[1 - u_x\left(1 + \frac{p}{a}\right)\right]\right\}\left\{\mathrm{NN_E} - \right.$$
$$\left.\left\{(u_x + 1)\, e^{\,\varphi(t - t_x)}\left[\frac{af + rp}{a} + \frac{r(f - r)\mathrm{N_E}}{a\mathrm{N}}\right] - u_x\left(1 + \frac{p}{a}\right)\left(f - r\right)\right\} \mathrm{N_E^2}\right.$$

However, determinations of the values of the coefficients and the knowledge of N and $\mathrm{N_E}$ in the ionosphere show that

$$a > p > 0;\; f > r > 0;\; a > r > 0 \text{ and } \mathrm{N} > \mathrm{N_E} > 0$$

whence

$$\frac{af + rp}{a} > \frac{r(f - r)\mathrm{N_E}}{a\mathrm{N}} \qquad \text{and} \qquad 1 > \frac{p}{a} = 0.01$$

Consequently, for the purpose of numerical computations, equation (V.85) can be written to an excellent approximation as

$$\frac{\partial \mathrm{N_E}}{\partial t} = -\left[a + p(1 - u_x)\right]\mathrm{NN_E} - \left[(u_x + 1)\, e^{\,\varphi(t - t_x)}\,\frac{af + rp}{a} - u_x(f - r)\right]\mathrm{N_E^2} \quad (\mathrm{V}.86)$$

Furthermore, since

$$f = 2 \cdot 10^{-11} \text{ cm}^3 \text{ sec}^{-1}; \quad \frac{af + rp}{a} = 2 \cdot 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$$

$$\text{and } (f - r) = 1.8 \cdot 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$$

we can write the preceding equation in the simpler approximate form

$$\frac{\partial N_E}{\partial t} = - [a + p(1 - u_x)] N N_E - [(u_x + 1) e^{\varphi(t - t_x)} - u_x] N_E^2 \qquad (V.87)$$

Equation (V.87) is always applicable for a value of $t - t_x$ such that the condition (V.83) is realized. In other words, if

$$0 < t - t_x < \frac{1}{(a + p)N + (f - r)N_E} \log_e \frac{aN + u_x [pN + (f - r)N_E]}{[pN + (f - r)N_E](u_x + 1)} \qquad (V.88)$$

we have a law of local variation of the electron concentration expressed in a general form by (V.85) or in a simplified form by (V.87). The latter is written

$$\frac{\partial N_E}{\partial t} = - \beta N_E - \alpha N_E^2 \qquad (V.89)$$

by setting

$$\beta \equiv [a + p(1 - u_x)] N$$

and

$$\alpha \equiv f[(u_x + 1) e^{\varphi(t - t_x)} - u_x]$$

where β/N denotes the coefficient of attachment of electrons and α denotes the effective recombination coefficient.

Let us note that the value of α will be comprised between the following values fixed by the condition (V.83), taking (V.84) into account

$$f \leqslant \alpha < f \frac{aN}{pN + (f - r)N_E} \qquad (V.90)$$

Consequently, if $t - t_x$ is sufficiently small, α may be greater than β/N_E and a variation of the electron concentration subject to a law of attachment results for a fixed value of N, i.e., at a given level z.

If $t - t_x$ increases beyond a certain limit, while the conditions imposed by (V.83) are met, the second term of relation (V.87 or 89) acquires an increasingly greater importance with respect to the first term, which diminishes. Hence, for a suitably chosen value of N, the variation of the electron concentration is subject to a recombination law $(\alpha N_E > \beta)$.

Case 2. Let us consider the reverse of condition (V.83), i.e.,

$$\frac{[pN + (f - r)N_E](u_x + 1) \, e^{[(a + p)N + (f - r)N_E](t - t_x)}}{aN + u_x[pN + (f - r)N_E]} > 1 \qquad (V.91)$$

a condition which for an arbitrarily chosen $t - t_x$ interval will be realized if N is sufficiently large (hence at a certain level), N being present in the exponential term.

If (V.91) is met, we have a fortiori

$$\frac{[pN + (f - r)N_E](u_x + 1) \, e^{[(a + p)N + (f - r)N_E](t - t_x)}}{aN - u_x[pN + (f - r)N_E]} > 1 \qquad (V.92)$$

and

$$\frac{aN(u_x + 1) \, e^{[(a + p)N + (f - r)N_E](t - t_x)}}{aN - u_x[pN + (f - r)N_E]} > 1 \qquad (V.93)$$

since $aN > pN + (f - r) N_E > 0$ and $u_x > 0$.

By virtue of conditions (V.92 and 93), we obtain from the solution of (V.80) of the Riccati equation, the approximate value of u

$$u = \frac{aN}{pN + (f - r)\bar{N}_E} \qquad (V.94)$$

which would be the stationary value of u determined by relation (V.71) if $\overline{N}_E$ were the stationary value of N_E.

By replacing u in equation (V.67) by its value (V.94), we obtain the relation

$$\frac{\partial N_E}{\partial t} = - \frac{a(f-r)NN_E^2}{pN + (f-r)N_E} - \frac{(a+p)N + (f-r)N_E}{pN + (f-r)N_E} \, rN_E^2 \qquad (V.95)$$

where the time interval t - t_x is chosen under conditions (V.91, 92 and 93) so that it will be possible to neglect, as before, the fluctuation $\triangle N_E$ of N_E in this interval.

Two cases of interest for ionospheric applications may be considered according to the relative values of the two terms in the denominator.

Let pN < (f - r) N_E. Equation (V.95) is then written in the approximate form

$$\frac{\partial N_E}{\partial t} = - \frac{af}{f-r} \, NN_E - rN_E^2 \qquad (V.96)$$

If pN > (f - r) N_E, a case readily achieved for the conditions imposed, since N must be chosen to be sufficiently large (condition V.91) and hence, z must be sufficiently low, we have

$$\boxed{\frac{\partial N_E}{\partial t} = - \frac{af + rp}{p} \, N_E^2} \qquad (V.97)$$

which yields a recombination law.

Consequently, if the value of t - t_x is conveniently chosen for a sufficiently high value of N (relatively low altitude), the law of local electronic variation will be a recombination law.

By considering the numerical values of the coefficients, we shall see that the various simple laws which have just been established on

the basis of our general laws (V.1, 2, 3) apply to the vrious iono-
spheric regions.

The E Region

In the E region we have $N > 10^{12}$ and $N_E \leqslant 2 \cdot 10^5$. Let us recall

the mean values of the coefficients a = $2 \cdot 10^{-14}$ cm^3 sec^{-1}, p = $2 \cdot 10^{-16}$

cm^3 sec^{-1}, f = $2 \cdot 10^{-11}$ cm^3 sec^{-1} and r = $2 \cdot 10^{-12}$ cm^3 sec^{-1}.

In this case, we see that for $t - t_x$ = 100 seconds, condition

(V.91) is fulfilled, even if u_x = 0, and we find ourselves in the theo-

retical Case 2 considered above. In addition, $pN > (f - r)N_E$, and con-

sequently we can apply (V.97). The latter is written, when the coeffi-
cients are replaced by their numerical values, as

$$\frac{\delta N_E}{\delta t} = -2 \cdot 10^{-9} N_E^2 \qquad (V.98)$$

Consequently, the law of the nocturnal variation of the electron
concentration in the E region is always a recombination law whose con-
stant coefficient within the layer has an average value of the order of

$2 \cdot 10^{-9}$ cm^3 sec^{-1}. This figure agrees well with the experimental values

(see Chapter I, p. 19) where α = 2 to $4 \cdot 10^{-9}$.

We see from this result that the effective recombination coeffi-
cient exceeds the values deduced from elementary physical processes.
Although one could expect a law of attachment for the higher molecular
concentrations, one actually finds a recombination law which, in addi-
tion, is in excellent agreement with ionospheric observations. This
result is readily interpreted when equation (V.97) is examined, where
the recombination coefficient of the positive and negative ions f is
multiplied by the constant ratio a/p. This ratio corresponds to a
higher value u_M (V.72) of u = N^-/N_E (ratio of the concentrations of

negative ions and electrons). Effectively, by returning to the value
of u indicated in equations (V.71 and 94), where we take into account
the condition $pN > (f-r) N_E$ valid in the E region, we find that the

stationary value (V.71) is then identical to the value (V.94). In other words, a state of equilibrium between negative ions and electrons tends to be established very quickly in the E region (< 100 seconds).

Hence, it follows from the observational standpoint that the processes of attachment and detachment of electrons occur without the introduction of a perturbation by the direct recombination of positive ions with electrons. A ratio of electrons to negative ions corresponding to a permanent equilibrium may be established and preserved in the course of the occurrence of the recombination phenomenon. This dynamic equilibrium between particles of negative charge causes the variation of the electron concentration in the E region to be independent of the attachment or detachment of electrons and to follow a recombination law whose effective coefficient exceeds that of the elementary processes.

Finally, the value $2 \cdot 10^{-9}$ is the maximum value obtainable by an effective night recombination coefficient.

The F Regions

In order to apply the preceding theoretical relations to the F regions, we have to consider all the numerical values of N and N_E. To this end, we have calculated the values of the exponential

$$e^{[(a + p)N + (f - r)\bar{N}_E](t - t_x)}$$

for different values of N and N_E. The computation has been made for

values of the time interval, $t - t_x$, comprised between 1 and 10^4

seconds. The average values of N_E considered are equal to 10^4, 10^5 and

10^6 electrons per cm^3, and thus cover all the observable values of the

electron concentration. By taking atomic concentrations between 10^{14}

and 10^6, we are sure a priori of having considered the entire ionospheric

region. We have already stated that in the E region, $N > 10^{12}$. As far as the F regions are concerned, an indication is provided by the observational data of F. L. Mohler which we have presented in explicit form in relations (I.11 and 12). Effectively, if we consider the value of

the attachment coefficient, $a = 2 \cdot 10^{-14}$, at 360 km and at 270 km, we

obtain the atomic concentrations $N = 10^9$ at 360 km and $8.5 \cdot 10^9$ at 270 km.

The altitude of 360 km corresponds to the ionization maximum of the F_2 region. By adopting a value of N of the order of 10^{10} for the F_1 region which has disappeared in the course of the night, we can establish the region of the F_2 layer at 10^{10} and 10^8 atoms per cm^3 subjected to attachment. Hence, we see immediately that the law of local electronic variation pertaining to the F regions is represented by relation (V.87) which, when the coefficients are replaced by their numerical values, is written as

$$\frac{\partial N_E}{\partial t} = - [2 \times 10^{-14} + 2 \times 10^{-16} (1 - u_x)]NN_E$$
$$- \left[(u_x + 1) \ e^{(2.02 \times 10^{-14} N + 1.8 \times 10^{-11} N_E)(t - t_x)} - u_x \right] 2 \times 10^{-11} N_E^2$$

(V.99)

The first conclusion which follows from an inspection of this relation is that the minimum value of the recombination coefficient in the F regions will be $0.2 \cdot 10^{-10}$. In other words, if the absolute value of the term corresponding to the attachment is very low, the electronic variation will be subjected to a recombination law whose coefficient cannot be lower than $2 \cdot 10^{-11}$. This result explains the fact that the minimum values reached during most diverse observations is never lower than this value (see page 32).

The disappearance of the F_1 region—$(N_E)_{max}$ in the F_1 region $<$ $(N_E)_{max}$ in the E region—is very easily explained. Observations show that when the solar influence decreases (i→0), i.e., tends toward the case which we are considering (i ≡ 0), this region is no longer observable. In the F_1 region, where $N_E = 3 \cdot 10^5$ and $N \sim 10^{10}$, we see that the attachment surpasses the recombination. Since the attachment is proportional to the atomic concentration and its value is relatively high, this region disappears as soon as its altitude increases above a certain limit. We shall return to this point in a discussion of the diurnal conditions (Section 5).

As far as the F_2 region is concerned, we consider two extreme

cases which enable us to estimate the value of the different terms in the preceding relation. If $N = 10^9$, we have for

$$\overline{N}_E = 10^6, \quad \beta/\overline{N}_E = 2 \cdot 10^{-11}$$
$$\overline{N}_E = 10^5, \quad \beta/\overline{N}_E = 2 \cdot 10^{-10}$$

and the recombination coefficient is $2 \cdot 10^{-11}$.

If $N = 10^8$, and

$$\overline{N}_E = 10^6, \quad \beta/\overline{N}_E = 2 \cdot 10^{-12}$$
$$\overline{N}_E = 10^5, \quad \beta/\overline{N}_E = 2 \cdot 10^{-11}$$

and the recombination coefficient is $2 \cdot 10^{-11}$.

These data reveal the diverse special properties of the F_2 region.

(1) A value of the observed recombination coefficient which varies in accordance with the distribution of the constituents. Indeed, the analysis of the observations always conforms to a law of the form

$$\frac{\partial N_E}{\partial t} = -\alpha' N_E^2$$

whereas the theoretical law is of the form

$$\frac{\partial N_E}{\partial t} = -\alpha N N_E - \alpha N_E^2$$

whence

$$\alpha' \equiv \frac{\alpha N}{N_E} + \alpha$$

is an apparent recombination coefficient.

(2) If the value of N_E at a given altitude varies with the epochs, we obtain variable values of the apparent recombination coefficient. In fact, we find that a decrease or increase of the electron concentration is associated with an increase (or decrease) of the equivalent recombination coefficient. Thus, observations which during the same night reveal variations of the coefficient are easily explained by the opposite variations of N_E. Similarly, variable values of the same

coefficient in the course of the seasons are due to the same cause.

(3)   The conclusion which we have drawn (page 33) to the effect
that there were pronounced differences in the values of the recombina-
tion coefficients during the observations of Appleton, on the one hand,
and Mohler, on the other, can be interpreted in the light of the result
acquired on the effect of the electron concentration.   Whereas the ob-
servations made in 1933-34 pertain particularly to low electron concen-
trations (minimum solar activity), the observations of 1937-38 indicate
high concentrations.   Hence, we have a low equivalent recombination
coefficient for 1937-38 and a high coefficient for 1933-34.

(4)   The effect of the altitude on the values of the recombination
coefficient is interpreted in the same manner.   According to the values
of the ratio of the atomic to the electron concentrations, the coeffi-
cient will be subject to fluctuations.   For the same value of N_E, the

coefficient will decrease with the altitude.   In other words, if the
altitude of the maximum electron concentration of the F_2 region is dif-

ferent at two stations, its equivalent recombination coefficient for
the same electron concentration will be directly proportional to the
number of neutral atoms.

(5)   The fact that the law of attachment is initially more impor-
tant than the law of pure recombination causes a more rapid decrease of
the electron concentration in the lower layers of the F_2 region.   During

the first part of the night, one observes indeed a rise in the altitude
of the maximum concentration of the F_2 region.

(6)   While the altitude of the F_2 region increases, the number of

atoms decreases with the altitude and the attachment becomes increasingly
less important.   During this time, the recombination coefficient in-
creases gradually toward a value equal to, then greater than the product
of the number of electrons by the coefficient of attachment.   From that
moment on, the altitude of the F_2 region can no longer rise, since the

effect of the molecular concentration no longer intervenes.   This is a
good explanation for the observed fact that the maximum altitude of the
F_2 region is reached for a recombination coefficient always greater than
$2 \cdot 10^{-11}$.

(7)   These various considerations suggest an explanation for the
origin of the numerous fluctuations in the F_2 region.   Indeed, this is

an atmospheric region where the effects of electron recombination and

attachment are simultaneously involved. If we add that the coefficients which we have considered to be constant are temperature-dependent, we can state that slight modifications of the molecular concentration or temperature cause the observed fluctuations in the ratio of the relative values of the two processes of attachment and recombination. Finally, the electron concentration itself being also a factor, it is easy to understand that the complexity of the phenomena taking place in the F_2 region depends primarily on the relations affecting the elementary mechanisms.

(8) These results also suggest that the abnormal behavior patterns observed will have to be studied by taking into account the particular characteristics of the F_2 region. In fact, new observations should provide simultaneous data on the variations in the electron concentration and actual altitude.

Section 5. Diurnal Conditions

During the transition from nocturnal to diurnal conditions, the solar radiation causes a modification in the processes affecting the electron concentration. This modification is due a priori to photoionization and, depending upon the circumstances, to photodetachment. We have shown in a study (in Section 2 of this chapter) of the formation of an ionized region that the electron production by photoionization should be considered to be the most important phenomenon. Furthermore, the photoionization of specific molecules or atoms characterizes the various regions of the ionosphere (Section 3). Finally, the equilibrium between the processes corresponding to the elementary mechanisms of attachment and detachment varies with the altitude and was successfully determined by an examination made in Section 4 of the nocturnal ionospheric conditions. On the basis of these various acquired results, it is possible to determine the diurnal behavior of the ionosphere.[1]

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[1]In principle, it is sufficient to determine, from equations (V.1, 2, 3), the value of the ratio u of negative ions to electrons. As in the case of nocturnal conditions, we obtain a Riccati equation

$$(u+1)\left\{ uN_E\left[d + pN + (f - r)N_E \right] - aNN_E + Ni \right\} - Ni + N_E \frac{\partial u}{\partial t} = 0$$

whose particular solution is no longer the simple solution u = -1. Hence, we have simplified the problem by first examining stationary cases applied to each ionospheric region, whose main properties are known through the studies made in the preceding sections.

The E Region

In the E region, the molecule subjected to the photoionization effect is the O_2 molecule, and the negative ion is the oxygen atom.

Hence, equations (V.1, 2, 3 and 4) are written as

$$\frac{\partial N_E}{\partial t} = N(O_2)i + N^-(O)d - aN(O)N_E + pN(O)N^-(O) - rN^+(O_2)N_E \quad (V.100)$$

$$\frac{\partial N^+(O_2)}{\partial t} = N(O_2)i - rN^+(O_2)N_E - fN^+(O_2)N^-(O) \quad (V.101)$$

$$\frac{\partial N^-(O)}{\partial t} = aN(O)N_E - N^-(O)d - pN(O)N^-(O) - fN^+(O_2)N^-(O) \quad (V.102)$$

with

$$N^+(O_2) = N^-(O) + N_E \quad (V.103)$$

Let us set, (V.7),

$$u \equiv \frac{N^-(O)}{N_E}; \quad (V.104)$$

whence, (V.7'),

$$N^+(O_2) = (1 + u)N_E \quad (V.104')$$

In order to study the conditions under which the E region is formed, let us consider the general stationary state defined by (V.6). Taking (V.103 and 104) into account, and by analogy with (V.8, 9 and 10), we write equations (V.100, 101 and 102) as follows:

$$N(O_2)i_\infty e^{-\frac{zhN(O_2)}{\sinh\odot}} + [d + pN(O)]uN_E = aN(O)N_E + r(1 + u)N_E^2 \quad (V.105)$$

$$N(O_2)i_\infty e^{-\frac{zhN(O_2)}{\sinh\odot}} = (r + uf)(1 + u)N_E^2 \quad (V.106)$$

$$aN(O) = u[d + pN(O) + (1 + u)fN_E] \quad (V.107)$$

The equation (V.106) immediately yields the expression for N_E

$$N_E = \sqrt{\frac{N(O_2)i_\infty e^{-\frac{xhN(O_2)}{\sinh\odot}}}{(r + uf)(1 + u)}} \qquad \text{(V.108)}$$

The conditions necessary for a maximum of the electron concentration $(N_E)_{max}$ of the E region require that, (V.19),

$$pN(0) > d + (1 + u)fN_E \qquad \text{(V.109)}$$

and that, (V.17),

$$u = \frac{a}{p} \qquad \text{(V.110)}$$

We shall assume that the photodetachment is negligible (d coefficient), since relations (V.21 and 30), which admit the predominance of photodetachment, cannot represent an ionospheric region possessing the observed properties of the E region. Hence, we have to verify condition (V.109) numerically, where d is neglected. We have calculated the following average values (IV.59, 37 and 60), $a = 2\cdot10^{-14}$ cm^3 sec-1; $p = 2\cdot10^{-16}$; $f = 2\cdot10^{-11}$, and we have already indicated that $N_E \simeq 10^5$ and $N(0) > 10^{12}$. Consequently, condition (V.109) is verified in the E region.

Let us now return to the conditions of a maximum electron concentration, i.e., to expressions (V.20, 22, and 23) and we obtain, by using (V.108),

$$(N_E)_{max} = \sqrt{\frac{N_M(O_2)i_\infty e^{-1}}{\alpha}} (\sinh\odot)^{\frac{1}{2}} \qquad \text{(V.111)}$$

$$e = 2.718$$

with

$$\alpha = \frac{(a + p)(af + rp)}{p^2} \qquad \text{(V.112)}$$

$$u = \frac{a}{p} \, l, \qquad\qquad (V.113)$$

and

$$N_M(O_2)zh = \frac{N(O_2)zh}{\sinh_\odot} = 1 \qquad\qquad (V.114)$$

These are the fundamental relations which practically define the stationary state of ionization of the E region. Hence, it follows that the diurnal and nocturnal conditions should be identical as far as the mechanisms determining the ratio of the concentration of negative ions and electrons are concerned. Thus, despite the considerable importance of attachment indicated by the term $aN(O)N_E$ in equation (V.100), the

vertical distribution of the electron concentration (V.108) is subject to a recombination law. Actually, the following phenomenon takes place: while the solar radiation produces positive ions of molecular oxygen and electrons by ionization, the electrons are immediately captured by neutral atoms, and this association produces negative ions. However, the abundance of the latter cannot increase beyond a certain limit, since part of them disappear during the detachment by collision, which is proportional to the concentration of neutral particles. Since these processes of attachment and detachment are very rapid, an equilibrium between the negative ions and electrons is almost immediately established. Finally, if the general state is stationary, the recombination of positive and negative ions balances the production of electrons by photoionization.

When the state is not stationary, observation gives a law of variation of the electron concentration which is written as

$$\frac{\partial N_E}{\partial t} = P - \alpha N_E^2 \qquad\qquad (V.115)$$

where P is the electron production and α is the recombination coefficient. On the other hand, based on (V.100 to 104), the theoretical expressions are written as

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[1]For the determination of u, we have only considered the effect of the oxygen atom. In order to obtain a better precision, we should take into account the effects of N and N_2 on the detachement. Hence, the value of u could be somewhat lower, but the conclusions remain valid in all cases. Besides, the object of our work is to point out the essential ideas.

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$$\frac{\partial N_E}{\partial t} = N(O_2)i + uN_E\left[d + pN(O)\right] - \alpha N(O)N_E - r(1 + u)N_E^2 \qquad (V.116)$$

$$\frac{\partial N^+}{\partial t} = (1 + u)\frac{\partial N_E}{\partial t} + N_E\frac{\partial u}{\partial t} = N(O_2)i - (r + uf)(1 + u)N_E^2 \qquad (V.117)$$

$$\frac{\partial N^-}{\partial t} = u\frac{\partial N_E}{\partial t} + N_E\frac{\partial u}{\partial t} = \alpha N(O)N_E - uN_E\left[d + pN(O) + (1 + u)fN_E\right] \qquad (V.118)$$

This system of equations is too complex and cannot be reduced to a simple form corresponding to the law applied to the observations. Simplifiying hypotheses do not lead to any new conclusions. We thus have to consider the limiting case corresponding to the stationary state where, by virtue of (V.108 and 111), we have

$$N(O_2)i \equiv P \qquad (V.119)$$

$$(r + uf)(1 + u) \equiv \alpha \qquad (V.120)$$

and, for the maximum electron concentration,

$$P \equiv N_M(O_2)i_\infty e^{-\iota} \sin h_\odot \qquad (V.121)$$

Relation (V.111) defines the diurnal ionization state of the E region and thus permits a comparison with the experimental results. We have seen in Chapter I that the observations are best represented by a value of the recombination coefficient in excess of $2 \cdot 10^{-8}$ (see also Figure 6, p. 23). Moreover, during solar eclipses, the ratio of the decrease in the electron concentration between the first and second contact and the appearance of a minimum electron concentration in the middle of totality require recombination coefficient values in excess of 10^{-7}. The theoretical value of the recombination coefficient is given by expression (V.112). Let us also recall the numerical values calculated for average conditions in Chapter IV (IV.59, 37, 60 and 57)

$$a = 2 \cdot 10^{-14}; \quad p = 2 \cdot 10^{-16}; \quad f = 2 \cdot 10^{-11} \text{ and } r = 2 \cdot 10^{-12}.$$

We therefore have for α

$$\alpha = 2 \cdot 10^{-7} \qquad\qquad (V.122)$$

The value of this coefficient is, therefore, of the order of magnitude of the observed coefficient.

Let us recall, however, that the values of the coefficients of diurnal or nocturnal recombination correspond to a fixed physical state. In addition to the lack of precision in the determination, one cannot overlook the variations resulting from the fact that the physical conditions of the upper atmosphere differ with the latitude, the altitude and even the seasons.

From this relatively high value of the effective recombination coefficient, we deduce that the value of $\delta N_E / \delta t$ is low during most of the day as compared to the absolute values of the electron production and recombination. Thus, the equilibrium is practically reached at any instant t. This is in good agreement with the experimental results (Figure 2, p. 16) where

$$(N_E)_{max} = C(\sinh_\odot)^{1/2}$$

Finally, in Chapter IV, we have determined the value of i_∞ of O_2 (IV.24), and in Chapter V, the number of molecules $N_M(O_2)$, (V.62). Hence, from (V.111), if $\sinh_\odot = 1$, and $T_S = 6,000^\circ$, we find

$$N_E = \left(\frac{2.5 \cdot 10^{10} \cdot 2.8 \cdot 10^{-7}}{2.718 \cdot 2 \cdot 10^{-7}} \right)^{1/2} = 10^5 \qquad\qquad (V.123)$$

This value of the electron concentration is of the order of magnitude of the electron concentration observed in the E region.

The F_1 region

The diurnal behavior of the ionization state of the F_1 region is partly identical to that of the E region. Indeed, the existence of the F_1 region is observed at equatorial latitudes throughout the year, whereas at high and middle latitudes, the region persists only for heights of

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the sun of the order of $45°$. In other words, the F_1 region appears only when the altitude is lowest, and in this case it possesses properties analogous to those of the E region. It is therefore necessary, taking into account the conditions specified in Section 2, to assume that the diurnal ratio u of the concentration of negative ions to that of the electrons is constant.

We have shown (Section 3) in the determination of the origin of the ionospheric regions that the oxygen and nitrogen atoms are responsible for the formation of the F_1 region. Hence, the general formulas (IV.1, 2, 3) applied to these two atoms are written[1]

$$\frac{\partial N_E}{\partial t} = N(O)i(O) + N(N)i(N) + N^-(O)d + p\left[N(O) + N(N)\right]N^-(O) \quad (V.124)$$

$$- aN(O)N_E - r_1N^+(O)N_E - r_2N^+(N)N_E$$

$$\frac{\partial N^+(O)}{\partial t} = N(O)i(O) - r_1N^+(O)N_E - f_1N^+(O)N^-(O) \quad (V.125)$$

$$\frac{\partial N^+(N)}{\partial t} = N(N)i(N) - r_2N^+(N)N_E - f_2N^+(N)N^-(O) \quad (V.126)$$

$$\frac{\partial N^-(O)}{\partial t} = aN(O)N_E - N^-(O)d - p\left[N(O) + N(N)\right]N^-(O) \quad (V.127)$$

$$- f_1N^+(O)N^-(O) - f_2N^+(N)N^-(O)$$

Since

$$N^+(N) + N^+(O) = N^-(O) + N_E \quad (V.128)$$

we have, by setting

$$u \equiv \frac{N^-(O)}{N_E} \quad (V.129)$$

$$(1 + u)N_E = N^+(N) + N^+(O) \quad (V.130)$$

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[1] If N_2 were actually involved in the ionization of F_1, the theoretical consideration would be wholly applicable.

In addition, let us set

$$\frac{N(N)}{N(O)} \equiv w \qquad (V.131)$$

Taking (V.128 to 131) into account, we write equations (V.125 to 127) for a stationary state

$$N(O)i(O) = (r_1 + uf_1)N^+(O)N_E \qquad (V.132)$$

$$N(N)i(N) = (r_2 + uf_2)N^+(N)N_E \qquad (V.133)$$

$$aN(O) = u\{d + p[N(O) + N(N)] + f_1N^+(O) + f_2N^+(N)\} \qquad (V.134)$$

In the case of stationary state, relation (V.20) imposes the condition[1]

$$p[N(O) + N(N)] > f_1N^+(O) + f_2N^+(N) \qquad (V.135)$$

and

$$u = \frac{aN(O)}{p[N(O) + N(N)]} = \frac{a}{(w+1)p} \qquad (V.136)$$

Whence

$$N_E = \sqrt{\frac{N(O)i(O)}{(1+u)(r_1 + uf_1)} + \frac{N(N)i(N)}{(1+u)(r_2 + uf_2)}}$$

From these theoretical considerations we immediately infer that the term fN^+N^- is less important in the F_1 region than in the E region because the negative ions of nitrogen do not exist, and the recombination between N^+, O^+ and O^- is weaker than between O_2^+ and O^- (cf. IV.61).

The possibility of condition (V.135) and also a lower value of the recombination coefficient should thus result. Unfortunately, these theoretical considerations can only be qualitative, since it is impossible to determine the values of f_1 and f_2 and of the ratio w given by (V.131) without an arbitrary hypothesis.

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[1] In order to facilitate the notation, it is implicitly assumed that the coefficient p is the same for O and N.

The experimental value of the recombination coefficient has not been determined very precisely, but it is of the order of or less than 10^{-8}. By adopting this value, we are able to determine an order of magnitude for the electron concentration. If we consider the simple case (V.40)

$$N_M(0) = 2.3 \cdot 10^{10}$$

and (IV.28)

$$i_{\infty} = 7.8 \cdot 10^{-8}$$

we immediately obtain

$$(N_E)_{max} = \sqrt{\frac{N_M i_{\infty}}{e\alpha}} = 2.6 \cdot 10^5 \qquad (V.138)$$

a value which agrees with the observed values of the electron concentration of the F_1 region.

Let us now return to the condition (V.135) necessary for an interpretation of the diurnal behavior of the F_1 region. This condition is met so long as the sun is located at an angle of altitude relatively high above the horizon; i.e., when the altitude of the F_1 region is at its minimum.

When the sun is very low (at sunset or in winter), the altitude of the region increases while the pN factor diminishes until it becomes negligible. From that moment on, the conditions change and we find again the nocturnal conditions, where we have seen that

$$pN < (f - r)N_E$$

At this stage, the law of attachment causes the disappearance of the F_1 region as we have shown in Section 4.

In other words, the F_1 region is formed in a transition zone of the ionosphere separating two regions where the properties pertaining to the equilibrium of negative ions and electrons are different. In the E region, we have an effective recombination coefficient such that the

electron attachment has no effect on the vertical distribution of the electron concentration. On the contrary, in the F_2 region, the nocturnal conditions have revealed the effect of attachment on the variation and vertical distribution of the electron concentration. Hence, a peculiar situation of the F_1 region results between the E and F_2 regions; depending on its altitude, the F_1 region is subjected to the laws of the E region or to those of the F_2 region.

A numerical application gives the following results:

$$pN > pN(0) = 2 \cdot 10^{-16} \cdot 2.5 \cdot 10^{10} = 5 \cdot 10^{-6} \qquad (V.139)$$

$$(f - r)N_E = 1.8 \cdot 10^{-11} \cdot N_E \qquad (V.140)$$

We see that for a concentration of $2.6 \cdot 10^5$ electrons (V.138), the values of the terms pN and $(f - r)N_E$ are of the same order of magnitude.

This numerical result confirms the preceding theoretical deductions.

The F_2 Region

The general law of nocturnal variation of the electron concentration has revealed the special properties of the atmospheric range corresponding to the F_2 region. Although we have not yet determined the origin of this region, we do know the process of its formation. Indeed, we can find no atom whose photoionization maximum is located at altitudes as high as that of the F_2 region; it is possible, however, by virtue of deductions in Section 2 (formulas V.34 to 38), to find a maximum electron concentration at an altitude in excess of that of the production maximum.

Let us return to expressions (V.34 to 38) and apply them to the oxygen atom. Let us denote by $N_{F_1}(0)$ the oxygen concentration at the altitude of the maximum electron concentration of the F_1 region, and by $N_{F_2}(0)$ the concentration of oxygen at the altitude of the maximum electron concentration of the F_2 region. We can then write, (V.36'),

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$$\frac{zh\mathrm{N_{F_2}}(O)}{\sinh_\odot} = \frac{r(u+1)}{(1+2u)(r+uf)} \qquad (V.141)$$

and if α is the recombination coefficient of the F_2 region, (V.36"),

$$\frac{zh\mathrm{N_{F_2}}(O)}{\sinh_\odot} = \frac{r(u+1)^2}{\alpha(1+2u)} \qquad (V.142)$$

with (V.20)

$$\frac{zh\mathrm{N_{F_1}}(O)}{\sinh_\odot} = 1 \qquad (V.43)$$

and (V.34)

$$u = \frac{u\mathrm{N_{F_2}}(O)}{(1+u)f\mathrm{N_E}} \simeq \sqrt{\frac{u\mathrm{N_{F_2}}(O)}{f\mathrm{N_E}}} \qquad (V.144)$$

when 1 is negligible compared to u.

From relations (V.142 and 143), we deduce

$$\boxed{\frac{\mathrm{N_{F_2}}(O)}{\mathrm{N_{F_1}}(O)} = \frac{r(u+1)^2}{\alpha(1+2u)}} \qquad (V.145)$$

which, if u is known, makes it possible to determine the properties of the F_2 region as a function of the data obtained on the F_1 region.

The expression of the maximum electron concentration of the F_2 region is given by (V.38) (uf $>$ r)

$$\boxed{(\mathrm{N_E})_{max} = \frac{i_\infty(O)\,e^{-\frac{zh\mathrm{N_{F_2}}(O)}{\sinh_\odot}}}{a}} \qquad (V.146)$$

In order to elucidate the meaning of the final expressions (V.145 and 146), let us consider the case of observations which are always represented by a law of the form

$$\frac{\partial N_E}{\partial t} = P - \alpha N_E^2 \tag{V.147}$$

where P is the electron production and α is the recombination coefficient. Let us express the condition of a maximum electron concentration in the stationary case by writing

$$\frac{\partial P}{\partial N} = \frac{\partial \alpha}{\partial N} N_E^2$$

In order to find the expression (V.141 or 142), we have to set

$$P \equiv N(O)i_\infty e^{-\frac{\varkappa h N(O)}{\sin h_\odot}} \tag{V.148}$$

and

$$\alpha \equiv \frac{a N(O)}{N_E} + r(1+u) = (1+u)(r+uf) \tag{V.149}$$

i.e., relation (V.147) in the explicit form should be written, (V.148 and 149), as

$$\frac{\delta N_E}{\delta t} = N(O)i_\infty - a N(O)N_E - r N^+(O)N_E \tag{V.150}$$

This equation, expression the ionization state of the F_2 region, corresponds to the general equation (V.1), where the terms corresponding to the photodetachment and detachment by collision are neglected in the presence of the term representing the photoionization.

The final expression (V.146) makes it possible to determine the orders of magnitude which may be attained by the electron concentration of the F_2 region. Let us note first that the exponential term rapidly approaches 1 with rising altitude of the F_2 region as a result of the decrease in the molecular concentration. Indeed, at the level of the F_1 region, we have, if $\sin h_\odot = 1$, (V.143),

$$e^{-\frac{\varkappa h N_{F_1}(O)}{\sin h_\odot}} = e^{-1} = 0.368$$

so that for all practical purposes we can always assume that the value
of the exponential terms is of the order of 1 in the F_2 region. Moreover,

this result indicates that the electron concentration in the F_2 region is

not a direct function of the height of the sun above the horizon.

The values of $i_\infty(0)$ have been determined (IV.27 and 28);

$$i_\infty(0) = 2.6 \cdot 10^{-8} \text{ to } 7.8 \cdot 10^{-8}.$$

Whence, the highest value of $(N_E)_{max}$ is given, (V.146), by

$$(N_E)_{max} = 1.3 \cdot 10^6 \text{ to } 3.9 \cdot 10^6.$$

These electron concentrations agree with the order of magnitude of
the observed concentrations.

Finally, since the value (V.144) of u is a function of the ratio
$N(0)/N_E$, we readily visualize the complexity of the variations of the

electron concentration by examining the fundamental relation (V.145).
We are no longer dealing, as in the E and F regions, with simple proper-
ties which are independent of the altitude (constant recombination coef-
ficient), but with properties which involve both molecular and electron
concentrations which are no longer independent variables. If we add
that the stationary case considered is a simple case for the F_2 region,

where equilibrium is not always reached (electron concentration in-
creasing with time), we have thus determined the origin of the extreme
complexity of the variations of the electron concentration in the upper
ionospheric region.

In conclusions, the F_1 and F_2 regions have their origin in the

photoionization of the same elements acted upon by the same solar radia-
tion. The F_1 region is formed at the level of maximum ionization owing

to an equilibrium between the production of electrons and the recombina-
tion whose coefficient is constant. The formation of the F_2 region at

an altitude greater than the altitude of the photoionization maximum re-
sults from the equilibrium between the production of electrons and the
recombination whose coefficient is a function of the altitude

(predominant attachment). This unexpected behavior—since one could assume a priori an attachment effect which is most important in the lower regions—is explained by the duality of the equilibrium between the mechanisms affecting the negative ions. In the E region and in the diurnal F_1 region, we obtain a constant ratio of the concentrations of

negative ions to those of the electrons. In the nocturnal F_1 region and

in the F_2 region, the same ratio actually depends on the atomic and

electron concentration.

In other words, we have the following phenomena: during the production of electrons by photoionization, the electrons are captured by neutral particles possessing a sufficient electron affinity. The attachment, which is proportional to the concentration of the neutral particles, becomes more important the lower the altitude of the ionized region; it is, therefore, maximum for the E region and minimum for the F_2

region. The attachment is offset by detachments through collision with neutral particles and positive ions. In the E region and the diurnal F_1 region, the detachment by collision with neutral particles, which is

therefore proportional to their concentration, is the most important. An equilibrium results between the attachment and detachment of electrons to and through neutral particles, i.e., a dynamic equilibrium independent of the altitude, and in the final analysis, a constant effective recombination coefficient. This explains the formation of an ionized region (E region and diurnal F_1 region) at the level of the maximum

electron production. In the F_2 region, the collisions of negative ions

with positive ones are more effective than the collisions with neutral particles. In the case of an equilibrium, a ratio of negative ions to electrons results which is a function of the concentration of neutral particles, and, in the final analysis, an equivalent recombination coefficient which is no longer constant but decreases with the altitude. This explains the formation of an ionized region (F_2 region) at an altitude greater than that of the maximum electron production.

Section 6. Diurnal, Seasonal and Geographical Variations

From the study of diurnal conditions (Section 5) of ionization, it is easy to deduce the diurnal, seasonal and geographical variations.

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In the case of the E and F_1 regions, we have the simple law (V.23, 111)

$$(N_E)_{max} = \sqrt{\frac{N_M i_\infty}{\alpha e}} \ (\sinh_\odot)^{\frac{1}{2}} \tag{V.151}$$

$$e = 2.718$$

where N_M is the molecular or atomic concentration at the altitude of the photoionization maximum for a sun at the zenith. Hence, C being a constant, we have

$$\sqrt{\frac{N_M i_\infty}{\alpha e}} = C$$

and we write

$$(N_E)_{max} = C(\sinh_\odot)^{1/2} \tag{V.152}$$

This is permissible so long as the physical conditions remain the same, i.e., in particular, so long as N_M and i_∞ remain constant.

In the course of a day, at a given station, N_M and i_∞ may be considered constant (except in the case of strong perturbations) and (V.152) represents the diurnal electron variation in accordance with the observation (Chapter I, (I.1) and Figure 2).

If all the conditions remain identical in the course of the year, equation (V.152) applies. However, if the state of dissociation of O_2 in particular in the E region, and the solar emission i_∞ in general, undergo variations, the value of the constant may be different, and this explains the disagreements between the observation and the theoretical curves in Figure 4. We shall return to this point in the following section.

Furthermore, it will be readily accepted that the vertical distribution of the molecular and atomic concentrations is not the same at all latitudes. In particular, the dissociation equilibrium of O_2 cannot take place under the same conditions at the poles and at the equator. Hence, the ratio N_M/α will not be identical for all the stations, and

that is why for the same day of the year, the constant C will have values which will depend on the latitude. It is impossible to determine these values so long as the vertical structure of the upper atmosphere has not been studied along a meridian.

As far as the F_2 region is concerned, the diurnal, seasonal and geographical variations cannot be studied theoretically before the observation has been able to determine the exact altitude of the maximum electron concentration. In a study of nocturnal conditions (Section 4) and diurnal conditions (Section 5), we have sufficiently outlined the properties characteristic of this region.

Section 7. Eleven-Year Variation of the Ionization

If the origin of the various regions of the ionosphere is explained by the effect of well-defined solar radiations (Section 3), we still have to show that the variation of the emission of these radiations is capable of accounting for the variation of the ionization in the course of a period of an eleven-year solar activity. Two points should, therefore, be considered: (1) the intrinsic variation of the solar emission; (2) the variation of the maximum electron concentration of each ionospheric region.

From the laws giving the stationary values of the maximum electron concentration, we deduce for the E and F_1 region (V.151 and IV.21),

$$(N_E)_{max} \div \sqrt{i_\infty \sin h_\odot} = \sqrt{\varkappa Q \sin h_\odot} \qquad (V.153)$$

where $\varkappa$ is an average value of the absorption coefficient and where Q is the number of solar quanta producing the ionization,

and, for the F_2 region (V.146),

$$(N_E)_{max} \div i_\infty = \varkappa Q \qquad (V.154)$$

If we compare the values of the electron concentrations during a maximum $(N_E)_{max,M}$ and a minimum $(N_E)_{max,m}$ of solar activity, we obtain for the F_1 regions (V.153),

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$$\frac{(N_E)_{max,M}}{(N_E)_{max,m}} = \sqrt{\frac{Q_M}{Q_m}} \equiv S_{F_1} \tag{V.155}$$

provided that the same height of sun is considered.

For the F_2 region we write, (V.154),

$$\frac{(N_E)_{max,M}}{(N_E)_{max,m}} = \frac{Q_M}{Q_m} \equiv S_{F_2} \tag{V.156}$$

where the height of sun is not involved.

A comparison of expressions (V.155 and 156) gives the following relation, provided that the value of the electron concentration be reduced to a height of sun equal to 90°,

$$\boxed{S_{F_1}^2 = S_{F_2}} \tag{V.157}$$

since the ionization results from the absorption of the same solar radiations. Moreover, if we assume that, to a first approximation, the variation of the solar emission is the same in the spectral range between

λ 1000 Å and λ 900 Å,[1] we can write for the same height of sun (V.153 and V.155),

$$\boxed{S_E \simeq S_{F_1}} \tag{V.158}$$

Relations (V.157 and 158) are identical to relation (I.9), deduced from observational data, and thus determine the effect of the solar activity on the various ionized regions.

Let us now return to the experimental conditions which we examined in Chapter I, particularly in Section 3 and Figure 5, where we compared the variations of the solar emission based on arbitrary numbers of facular plages with the monthly variations of $(N_E)_{max}/\sinh_\odot$ of the

[1]Actually, there will always be a difference in the variations of the photospheric and chromospheric emissions, and S_E will be slightly different from S_F.

E region. In this particular case, we showed the parallelism between the two variations. Hence, by taking relations (V.153 and 154) and (V.157 and 158) into account, it is possible to define the ionospheric characteristics of the solar activity.

The relation between the critical frequency (observational data) and the electron concentration (see Introduction, formula 2.7) is given by

$$(N_E)_{max} = \varphi f_o^2 \qquad . \qquad (\text{V.159})$$

Moreover, we know (V.153) that when the conditions are stationary we have for the E and F_1 regions,

$$(N_E)^2_{max} \div \varkappa Q \sin h_\odot \qquad (\text{V.160})$$

and for the F_2 region

$$(N_E)_{max} \div \varkappa Q \qquad (\text{V.161})$$

Consequently, (V.159, 160 and 161), we have

$$C_E = \frac{(f_o^4)_E}{\sin h_\odot} \; ; \; C_{F_1} = \frac{(f_o^4)_{F_1}}{\sin h_\odot} \text{ and } C_{F_2} = (f_o^2)_{F_2} \qquad (\text{V.162})$$

where C_E, C_{F_1} and C_{F_2} define the ionospheric characteristics of the solar activity. Since stationary conditions always exist at noon for the E and F_1 regions, C_E and C_{F_1} are always defined. In the case of the F_2 region, the value of C_{F_2} cannot be well known unless the other variations play only a secondary role or could be eliminated.

The fact that the variation of the atmospheric ionization follows the variation of the number of facular plages and faculae makes it possible to attribute its origin to the variation of the continuous radiation of the faculae relative to that of the photosphere, and to the radiation of the facular plages relative to that of the chromosphere. In other words, during the solar activity minimum, the photospheric radiation ($\lambda > 910$ Å) and the chromospheric radiation ($\lambda < 910$ Å) originate

globally from the entire photosphere and from the entire chromosphere. However, during the solar activity maximum, the global radiation of the faculae and facular plages is the most important. We have shown (Figure 14) that if a temperature of $7,500^\circ$K is adopted for the faculae, and a total surface equal to 10^{-3} times that of the photosphere is assumed, the continuous radiation of the faculae in the spectral region of $\lambda\lambda$. 1000-910 $\overset{\circ}{A}$ is greater than that of the photosphere. This explanation makes it possible to understand the observational results according to which the ionization in the upper atmosphere is never related to the appearance or disappearance of a given spot (surface area $< 10^{-3}$ the area of the photosphere) but undergoes variations which are related to the global facular surface.

In the special case of a solar eclipse, where the fraction of the visible photospheric surface is markedly lower than the total surface, it is possible that the effect of a facula might influence the ionization of the E region. As an example, let us consider the solar edge at a temperature of $4,700^\circ$K and a facula of equal surface at $7,500^\circ$K. The ratio of the numbers of photospheric and facular quanta for $\lambda < 1000$ $\overset{\circ}{A}$ calculated with formula (II.3) is of the order of 10^{-5}. In other words, a facula at the edge of the sun may emit a radiation exceeding that of the visible fraction of the solar disk, if the surface is greater than 10^{-5} times that of the edge of the disk. Consequently, the effect of a facula which is close to the solar edge may reflect on the ionization of the E region, whereas the ionization of the F region, subjected to the chromospheric emission, will not be affected.

Section 8.   Perturbations of the Ionization State

Although it is possible to resort to simple notions such as photoionization and recombination in order to determine the ionization state of the various ionospheric regions, this is no longer the case when one deals with the problem of the origin of the various perturbations. The easy solution is to assume that the sun emits neutral or charged particles, depending upon the circumstances. Thus, for all the cases of nonuniformity of ionization (abnormal E region, sporadic ionization, ionospheric storm), one can accept as a working hypothesis the existence of neutral beams of charged particles such that their properties are suitable for observation. However, such a theory is a geometrical theory

in the sense that it determines the trajectory traveled by particles whose mass, charge and energy are adequate for explaining the effects observed in the atmosphere subjected to the action of the earth's magnetic field. However, no geometrical theory provides any indications on the transfer of energy from the incident particles to the atmospheric particles and on the possibilities of various forms of ejection of solar particles.

Actually, it is necessary to consider the fact that the equilibrium in the vertical distribution of the constituents of the upper atmosphere may be upset. For example, during an intense ionospheric (or magnetic) storm, marked modifications are observed in the distribution of the electron concentration. During the first phase, the zone corresponding to the normal electron concentration no longer exists, owing to a displacement of the electrons which steadily lowers the level of maximum concentration. This influence is a manifestation of an abnormal reduction in the thickness of the layer, as if the latter were subjected to an effect of turbulent disintegration. As a result of this phenomenon, an intense ionization occasionally appears below 100 km. As soon as the abnormal echo of this layer has disappeared, a marked increase is observed in the minimum of the virtual height of the F_2 region—an increase which may reach 800 km. This increase corresponds to a considerable decrease of the electron concentration, which drops from 10^6 electrons to about 10^3, as if the ionosphere had undergone a considerable expansion.

It is difficult to account for all these phenomena. Is there a vertical transport of the gaseous masses, a disappearance of the electrons through recombination, a decrease in the number of effective collisions, a transport toward the polar regions, or the opposite, an influence of the earth's magnetic field, a real expansion of the atmosphere? At the present time nothing is known about these questions. However, if we assume the arrival of solar particles or at least the separation of the particles with positive and negative charges in the highest region of the upper atmosphere, we also have to assume the existence of electric fields whose effects will be different depending upon the altitude, and which may produce the disaggregation of the normal ionosphere during critical conditions.

In view of the complexity of the theoretical study of this problem, and given the lack of quantitative observational data, simultaneous studies are necessary on the fine structure of the magnetic storm, ionospheric storms and auroral emission before any acceptable conclusions are drawn.

Section 9. Sudden Fade-Out

The difficulties which are encountered in an explanation of the ionospheric perturbations disappear as soon as it is possible to show that the abnormal ionization is due to ultraviolet radiations, not to charged particles. Such is the case of the sudden fade-out, whose properties were described in Chapter I.

The remarkable coincidence between the observation of a solar eruption and the appearance of a sudden fade-out in the sunlit hemisphere is proof of a direct effect of the electromagnetic radiation. The sudden cessation of the echoes of the E and F regions and the reinforcement of long waves are due to a sudden increase of ionization in the D region, where the molecular concentration is relatively high.

For this phenomenon to take place, it is necessary that a radiation of a particular intensity be emitted during an eruption. Furthermore, it is necessary that this radiation leave the ionization state of the E and F regions unaffected. Moreover, it should not be absorbed in the atmospheric region located above the D region. In addition, it should ionize a characteristic constituent of the atmosphere at an average altitude of 80 km. Finally, the nature of this radiation should be different from all those which determine the ionization state of the upper atmosphere.

On the basis of these criteria, we can ssume that a continuous emission related to the photospheric emission cannot be involved, since the spectrum of an eruption is essentially a line spectrum. It is evident that a chromospheric radiation with wavelengths of less than

910 $\overset{\circ}{A}$ should not be considered, since it is completely absorbed in the

F region. The radiation emitted in the range of 1000 to 910 $\overset{\circ}{A}$ can only

have a secondary importance, otherwise the radiations L_γ (972.6 $\overset{\circ}{A}$) and

L_ζ (930.8 $\overset{\circ}{A}$), located in the range of preionization bands of O_2, would

determine the ionization state of the E region.

The sudden fade-out should, therefore, result from the emission of

a radiation with wavelengths in excess of 1000 $\overset{\circ}{A}$. However, we have

shown (Chapter II, Section 3, D) that the radiation L_α (1,215.7 $\overset{\circ}{A}$)

during an eruption of a given surface and intensity can exceed the radiation of the continuous photospheric spectrum. Consequently, the

eruptive L_α radiation may emit quanta whose number is greater than that

of the normal photosphere and which can reach the atmospheric region located below the E region. However, in order to explain the fade-out, it is necessary to know the process by which the ionization undergoes the necessary increase. We must immediately eliminate the possibility of the atmospheric constituents, O_2, O, N_2, N, He which participate

in the ionization of the E and F regions and do not have an ionization

continuum at λ 1,215.7 $\overset{o}{A}$. Only the NO molecule (see Figure 15) can be photoionized by the L_α radiation. However, we have shown the existence

of this NO molecule (Chapter III) in the atmospheric region located below the E region. Hence, NO, localized in a region of small thickness located below the E region, may, under the influence of the L_α radia-

tion of the chromospheric eruptions, produce the increase in ionization necessary for a sudden fade-out.

GENERAL CONCLUSIONS

I. In order to formulate the problem of the determination of the structure of the ionosphere, we used as the basis the results acquired by mathematical and experimental studies of the propagation of electromagnetic waves in the ionized atmosphere acted upon by the earth's magnetic field. To this end, the introduction specifies exactly the adopted point of view, while the first chapter specifies in a synthetic form the ionospheric observational data. From this, we deduce that theoretical research on the physical properties of the ionosphere would require the knowledge of three factors:

1) The radiation emitted by the sun in the unobservable ultraviolet.

2) The chemical composition and the physical constitution of the entire atmosphere.

3) The knowledge of the ionization state of the atmospheric constituents subjected to solar radiation.

II. Usually, it is assumed in calculations that the sun radiates like a black body at $6,000°K$. The conventional nature of this working hypothesis forced us to make a thorough examination of the problem of the efficiency of the solar radiation in the atmosphere. This study enabled us to bring out, among others, the following points:

1) The solar ultraviolet emission is not confined solely to the photosphere, but also originates from the upper layers, particularly the chromosphere.

2) The spectral composition of the solar radiation may be determined on the basis of observations obtained during eclipses and by taking into account the chemical composition of the sun. Thus, we were able to show that the radiation emitted in the spectral range of wavelengths in excess of 910 Å corresponds to that of the photosphere, and that the chromosphere is characterized by radiation of wavelengths below 910 Å. Calculation shows indeed that the minimum intensity (for $\lambda < 910$ Å) of the chromospheric radiation is greater than that of a black body at $6,000°K$.

3) A priori, monochromatic radiations are superimposed on the photospheric radiation. We showed that the L_α line ($\lambda = 1,215.7 \overset{o}{A}$) of hydrogen may emit a number of quanta greater than that of the neighboring spectral range, while the other lines of the Lyman series play a negligible part to a first approximation.

4) The eleven-year activity, well-known through the variation of the spots, has its origin in the continuous radiation of the faculae relative to that of the photosphere and in the radiation of the facular plages relative to that of the chromosphere.

5) Chromospheric eruptions emit in particular a radiation of λ 1,215.7 $\overset{o}{A}$ whose intensity, depending on the circumstances, exceeds that of the continuous spectrum of $\lambda < 1,350$ $\overset{o}{A}$ of the unperturbed photosphere.

III. If we review the principal determinations of the composition of the atmosphere which is not accessible to aerological soundings, we find marked discrepancies in the results. Generally, the vertical distribution of the constituents is calculated by starting with the composition of the air at the surface of the ground and assigning conventional values to the temperature. We abandoned this method, which did not result in any satisfactory findings, and studied the distribution of the atmospheric constituents as a function of the rate of logarithmic decrease of their concentrations with the altitude.

By determining the state of equilibrium of the oxygen molecule in the field of radiation of the sun, we determined the region of dissociation of this molecule independently of any hypothesis. Hence, the maximum abundance of the oxygen atom is located at about 105 to 110 km at our latitudes.

From an examination of the elementary mechanisms simultaneously affecting the other constituents, we deduced the formation of the NO molecule and the production of the nitrogen atom. Moreover, we showed that this atom and this molecule are mutually exclusive. The range of NO is located above the zone of the dissociation maximum of O_2, whereas the presence of the nitrogen atom is permanent in the region of existence of the oxygen atom. Finally, helium is an element whose presence should be effective in the upper atmosphere.

IV. Before studying the ionospheric properties directly, we formulated the general equations of ionization. The different processes were determined theoretically and made applicable to the upper atmosphere. The numerical calculations have made it possible to determine fairly precisely the different coefficients corresponding to the photoionization, recombination, and attachment and detachment of electrons. With the exception of the case of photodetachment, the values obtained reveal the relative influence of the different coefficients in the ionization equations.

V. By approaching the general problems of a theoretical determination of the ionospheric properties, we tried to determine under what conditions an ionized region could be formed. Thus, by a comparison with the experimental data, we showed directly that the E and F_1 regions

can be interpreted only if the electron concentration maximum is located at the level of the maximum electron production by photoionization. On the contrary, the F_2 region can correspond only to an ionized region

where the maximum electron concentration is located at an altitude that is greater than that of the production maximum.

The above requirements enabled us to determine the origin of the ionized regions. The F region results from the ionization of oxygen and nitrogen atoms acted upon by chromospheric radiation with wavelengths

below 910 $\overset{\circ}{A}$. The other constituents, such as molecular nitrogen and helium, have their photoionization maxima at the same altitude as atomic oxygen and nitrogen. Moreover, the O_2 molecule, whose concentration is

very low at this altitude, also has a photoionization maximum due to the

absorption of its continuum of $\lambda < 735 \overset{\circ}{A}$. Finally, no radiation with

$\lambda < 910 \overset{\circ}{A}$ can reach the E region with a sufficient intensity. We also showed that the origin of the E region is due to the emission of photo

spheric radiation of 1000 $\overset{\circ}{A} < \lambda < 910 \overset{\circ}{A}$ which preionizes the oxygen molecule. This latter result shows that the state of logarithmic decrease of the concentration of the O_2 molecule with the altitude corresponds to

the ionospheric height scale of the E region. Finally, we came to the conclusion that the principal phenomenon below the E region results from the ionization of the NO molecule under the influence of solar radiation

with wavelengths of less than 1,350 $\overset{\circ}{A}$.

By determining the theoretical laws governing the nocturnal variation of the electron concentration, we showed that the laws of disappearance of electrons are radically different in the E and F regions. In the E region, the recombination coefficient is constant and has an average value of the order of $2 \cdot 10^{-9}$. On the contrary, in the F region, the coefficient is a function of the molecular concentration and of the electron concentration, and therefore depends on the altitude. This unexpected result explains the profound differences observed in the behavior of the two regions. The determination of the diurnal variation also enabled us to show that the F_1 and F_2 regions are due to the photo-ionization of the same elements under the influence of solar radiation of the same wavelengths. The F_1 region is formed at the level of the maximum photoionization owing to an equilibrium between the electron production and the recombination whose coefficient is constant. The formation of the F_2 region, at an altitude greater than that of the photoionization maximum, is due to the equilibrium between the electron production and the recombination whose coefficient is a function of the altitude (predominant attachment).

Since the attachment is proportional to the molecular concentration, this behavior is unexpected; one could have expected a major influence of the attachment in the lower regions E and F_1. Actually, the opposite takes place, since we have shown the duality of the equilibrium between the mechanisms affecting the negative ions.

Within the framework of the above determinations, we found it easy to identify the laws governing the seasonal variation of the E region and to give a qualitative explanation for the geographical variation.

The fluctuations and the eleven-year variation of the ionization under solar influence were interpreted. In particular, the electron concentration of the E and F_1 regions is proportional to the square root of the number of solar quanta absorbed, while the eleven-year activity of the F_2 region depends directly on the number of absorbed quanta.

Finally, after having indicated the path susceptible of providing the solution to the problem of ionospheric perturbations, we showed that the NO molecule makes it possible to explain the sudden fade-out by the increase in the ionization produced under the influence of L_α radiation of chromospheric eruptions.

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